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THESIS

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ITS CERENKOV RADIATION

by

Richard J. Phillips

December 1989

Thesis Advisor X.K. Maruyama

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Monte Carlo Generation of Cerenkov Radiation

by

Richard J. Phillips
Captain, United States Army
B.S., United States Military Academy, 1979

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PHYSICS

from the

NAVAL POSTGRADUATE SCHOOL
December 1989

ABSTRACT

The Integrated Tiger Series (ITS) code family, produced at Sandia National Laboratories, Albuquerque, NM, model the transport of electrons/photons. These codes are used in many applications such as radiation shielding and radiation dose prediction. A method of adding Cerenkov radiation to the output capabilities of the code was devised by Joseph Mack of Los Alamos National Laboratory and Thomas Jordan of Experimental and Mathematical Consultants. This method has been extended to include the effects of wavelength dependent indicies of refraction. The capability to handle air and carbon dioxide gas at different pressures and temperatures has been added to the program. The modifications to the code patch provide the user with wavelength information on the Cerenkov spectrum which shows 44 percent more production in the 1800 to 2000 angstrom wavelength bin than calculated by the Mack-Jordan patch. These additions to ITS provide a potentially valuable tool for design and implementation of Cerenkov detectors.

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I would like to give special thanks to Joseph Mack of Los Alamos National Laboratory for contributing his time and expertise to this project. This work is produced as an offshoot of his ideas.

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I. INTRODUCTION

Charged particle and photon transport are topics of much interest to the scientific community and have been for much of this century. Since Rutherford's work with scattering from thin foils, many new theories have been developed to predict the radiation and charged particle deposition caused by energetic beams of charged particles or photons diffusing through various materials. These theories describe the angular deflections of particles and the energy losses associated with the beam's passage.

Since the advent of the high speed computer, several computer codes have been developed to simulate the cascades caused by energetic electron beams impinging on different materials. A series of Monte Carlo codes that simulate the transport have been developed by Martin Berger and Stephen Seltzer at the National Bureau of Standards (NBS) over the past 25 years. These codes, such as ETRAN, form the basis for other codes written at laboratories across the United States. The ETRAN algorithm has been used by Sandia National Laboratory (SNLA), to develop the Integrated Tiger Series (ITS). The scheme of the random walk used in the ITS calculations has its roots in ETRAN. [Ref. 1]

ITS includes 8 different variants of a basic code. These codes reflect various combinations of geometries and some allow the superposition of electromagnetic fields. One of these, ACCEPT, allows the user to specify a combinatorial, fully general, three dimensional geometry. A beam of electrons or photons striking and diffusing through the target is simulated, including the cascade of secondary electrons and photons. The program tracks primary electrons or photons and all possible secondary radiations, including knock-on electrons, bremsstrahlung, Compton electrons, photoelectrons, electron-positron pairs, annihilation radiation, as well as K-shell characteristic x-rays and Auger electrons. Electrons and photons with energies between 1 keV and 1 GeV can be tracked. [Ref. 1]

Cerenkov radiation was not included in the ITS cascade since there was no need for its inclusion at the time the ITS codes were developed. However, for certain applications such as the design of Cerenkov detectors, its inclusion is required. This problem was addressed by Mack and Jordan. They produced a code patch to allow the ACCEPT code to simulate and track Cerenkov production. This addition to the code samples the Cerenkov production along a substep and then ray traces (there is no real transport for

these low energy photons) the Cerenkov light through the geometry, tallying that which arrives at the detector, and the Cerenkov photons produced and absorbed in each zone. The patch due to Mack and Jordan assumes a constant index of refraction for each material and no wavelength dependence. The present work compares the results of this method of Cerenkov sampling with the results produced by including the variable index of refraction for the materials in which the Cerenkov production and ray trace take place. The results of this comparison show 44 percent more production in the 1800 to 2000 angstrom wavelength bin than calculated with the constant index of refraction used for runs with the Mack-Jordan patch.

II. THEORY

A. HISTORY

While the exact date of the discovery of Cerenkov radiation is not known, we do know that Mme. Curie was among those to notice the uncanny, pale blue light given off from bottles of concentrated radium solutions. This observation was documented in 1910. In 1934, Frank and Tamm provided the correct explanation for this radiation. The long delay between the time when the radiation was first noted and the theoretical explanation of it was most likely due to the abundance of new discoveries in physics during the early years of this century, especially in the area of florescence and phosphorescence. Cerenkov radiation was so weak as to cause its effects to be masked by the presence of these other phenomena.

Mallet made the first deliberate attempt to study the phenomenon in the years 1926 through 1929. However, he failed to pursue the subject to completion. Then, in 1934, Cerenkov began a series of experiments which continued into 1938. His experiments were simple, yet they showed remarkable agreement with the theory developed by Frank and Tamm.

In 1940, Ginsburg produced a quantum theory of the phenomenon which was thereafter known as Cerenkov radiation. The radiation is called Cerenkov-Vavilov in the Soviet literature. In 1947, Getting proposed using a photomultiplier and an optical system for detecting single particles from the Cerenkov radiation. In 1951, Jelley was the first to detect, with high efficiency, single, fast charged particles. His work was followed closely by the published accounts of Mather and Marshall's work using Cerenkov detectors for the measurement of velocities of particles from high energy accelerators.

Since that time, a wide variety of uses have been found for Cerenkov detectors, including the discovery of the anti-proton, investigations of anisotropic media and ferromagnetics, as well as the measurement of energies released in nuclear explosions.

The Cerenkov effect is described as follows: [Ref. 2: pp. 5-6]

1. A free electron injected into a transparent medium produces a local polarization of the medium.
2. At small velocities this polarization is roughly spherically symmetric. This local polarization of the atoms causes them to behave like small dipoles, which revert to their original arrangement after the passage of the electron (or other charged particle). See Figure 1 on page 4. However, due to the spherical symmetry of the polarization field, there is no resultant field at large distances.

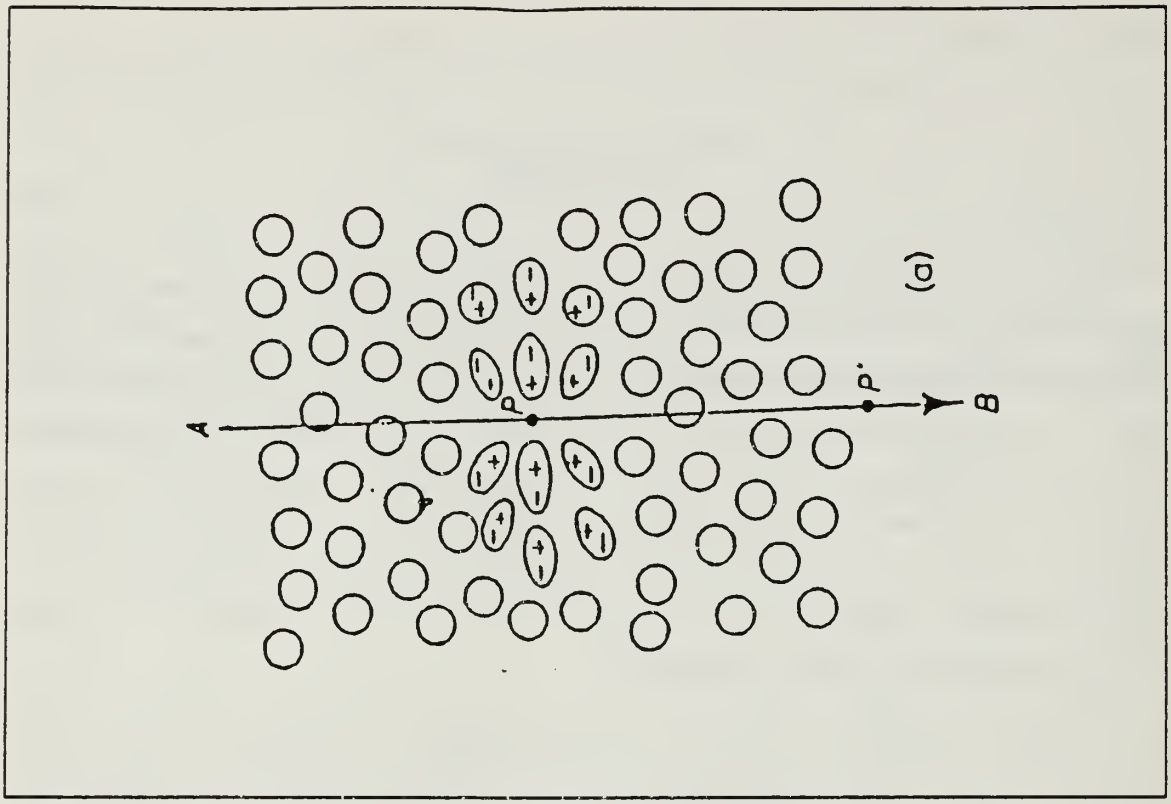

Figure 1. Local Polarization of Transparent Medium: [Ref. 2: pp. 5-6]

3. At greater velocities of the electron, the spherical symmetry of the polarization field is destroyed along the axis and radiation is emitted. In general, this radiation interferes with itself destructively so that there is no resultant field at large distances.
4. However, if the velocity of the electron is greater than the phase velocity of light within the medium, then there is an angle at which all of the wavelets from all portions of the electron track are in phase with one another so that there is a resultant field at a distant point. See Figure 2 on page 5 and Figure 3 on page 6.

The angle at which Cerenkov radiation is produced is defined by the Cerenkov relation,

$$\cos(\theta) = \frac{1}{n\beta} . \tag{2.1}$$

Cerenkov radiation is only produced above the velocity threshold defined by

$$\beta_{\min} = \frac{1}{n} , \tag{2.2}$$

where n is the index of refraction of the medium and β is the ratio of the electron velocity to the speed of light. The condition for Cerenkov radiation to occur is

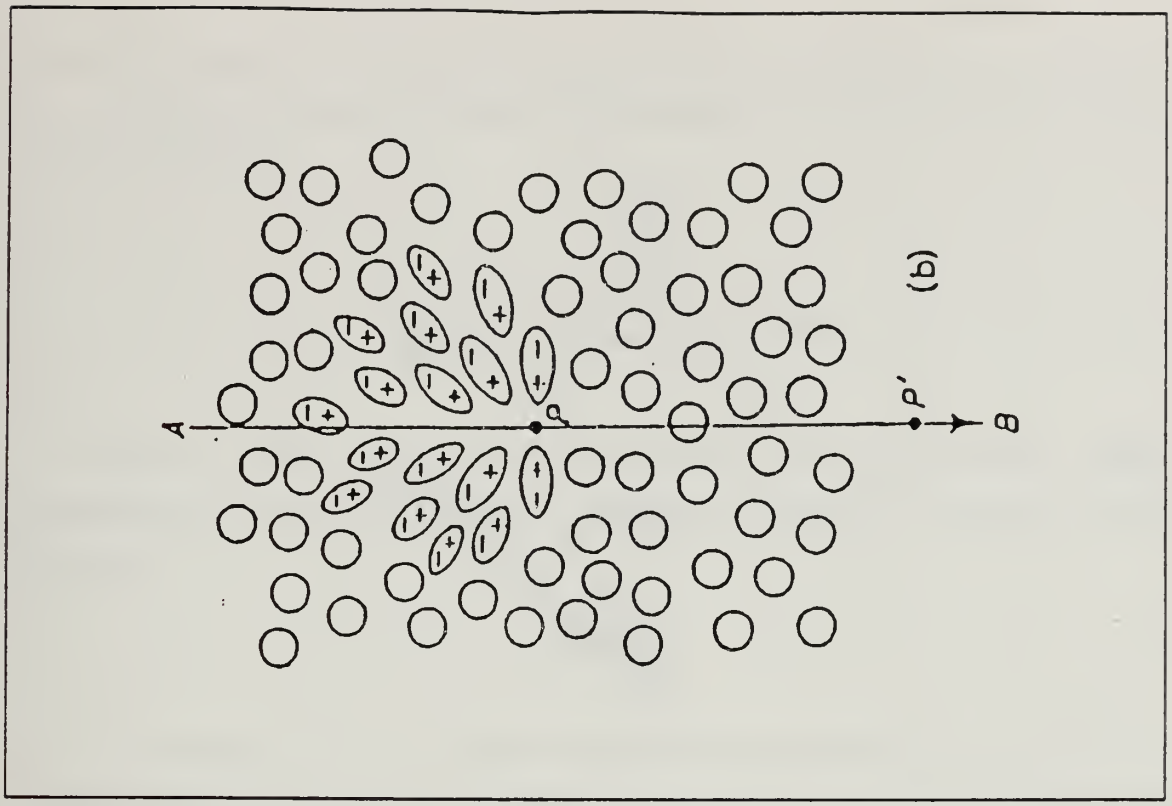

Figure 2. Arrangement of Atoms after Electron Passes: [Ref. 2: pp. 5-6]

$$n\beta > 1. \tag{2.3}$$

The angle of emission is defined by

$$\theta = \cos^{-1}\left(\frac{1}{\beta n}\right). \tag{2.4}$$

Cerenkov radiation occurs primarily in the visible and near ultraviolet regions of the spectrum, for which $n > 1$. Emission in the x-ray region of the spectrum is usually not possible since the index of refraction is then less than unity and the Cerenkov condition cannot be satisfied. (An exception is at absorption edges, where it is possible to obtain $n > 1$.)

Cerenkov radiation may be thought of as similar to the V shaped bow wave from a boat. The radiation comes off at a particular angle, defined by the index of refraction of the medium, the dominating wavelengths of the radiation, and the velocity of the charged particle. See Figure 3 on page 6. The wavelength of the radiation plays a part

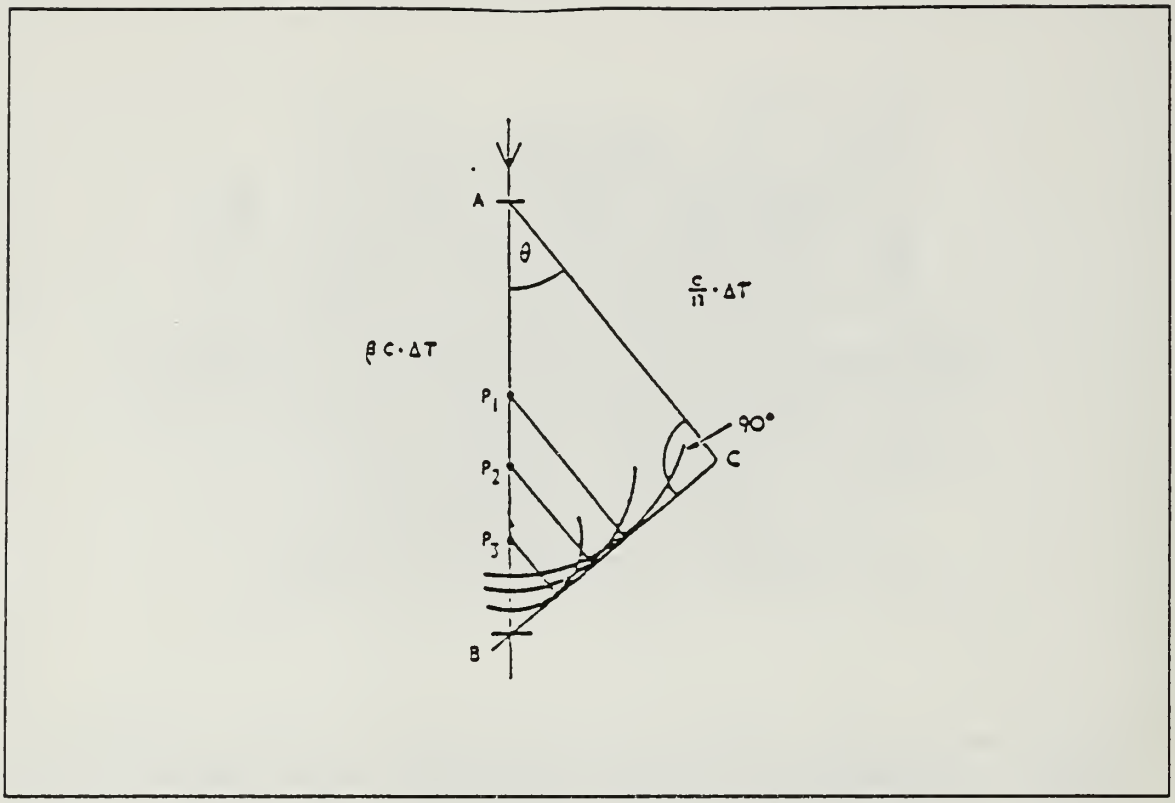

Figure 3. Cerenkov Angle: This figure shows the Cerenkov angle θ through the Huygens construction. [Ref. 2: pp. 5-6]

since the index of refraction for the medium is dependant upon wavelength. [Ref. 2: pp. 1-14]

B. THE CLASSICAL THEORY OF FRANK AND TAMM

In 1937, Frank and Tamm provided the first theoretical explanation for Cerenkov radiation. Their theory made the following assumptions: [Ref. 2: p. 15]

1. The medium is considered as a continuum, so that the microscopic structure is ignored: the dielectric constant is then the only parameter used to describe the behavior of the medium.
2. Dispersion is ignored, at least in the first approximation.
3. Radiation reaction is neglected.
4. The medium is assumed to be a perfect isotropic dielectric, so that the conductivity is zero, the magnetic permeability equal 1, and there is no absorption of radiation.
5. The electron is assumed to move at constant velocity; ie. the slowing down due to ionization, and the multiple Coulomb scattering are ignored.
6. The medium is unbounded and the track length infinite.

Using these assumptions, Frank and Tamm derived the equation for the output of radiation (cgs units).

$$\frac{dW}{dl} = \frac{e^2}{c^2} \int_{\beta n > 1} \left(1 - \frac{1}{\beta^2 n^2}\right) \omega d\omega \tag{2.5}$$

Without a cutoff frequency for the above integral, the output energy is infinite. However, since a real medium is always dispersive, the radiation is restricted to bands such that

$$n(\omega) > \frac{1}{\beta}. \tag{2.6}$$

Also, the absorption bands for higher frequencies limit the radiation to the near ultraviolet and lower frequencies. The refractive index is less than unity for frequencies in the x-ray region making Cerenkov radiation forbidden.

For constant βn we can express the radiation intensity in terms of the number of photons of wavelengths between λ_1 and λ_2 which are emitted by an electron.

$$N = 2\pi\alpha l \left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)\left(1 - \frac{1}{\beta^2 n^2}\right) \tag{2.7}$$

where α is the fine structure constant and l is the path length.

There are a variety of ways to express the spectral distribution of Cerenkov radiation. The intensity of light of frequency v may be written as

$$W = Nhv, \tag{2.8}$$

where N is the number of photons of that frequency, h is Plank's constant and v is the frequency. We can write the spectral distribution of Cerenkov radiation in the following four ways: [Ref. 2: pp. 15-22]

- Energy per unit path per unit frequency interval.

$$\left(\frac{d^2W}{dl\, d\omega}\right) \propto \omega \tag{2.9}$$

- Energy per unit path per unit wavelength interval.

$$\left(\frac{d^2W}{dl\,d\lambda}\right)\propto\frac{1}{\lambda^3} \tag{2.10}$$

- Number of photons per unit path per unit frequency interval.

$$\left(\frac{d^2N}{dl\,d\omega}\right)\propto Constant \tag{2.11}$$

- Number of photons per unit path per unit wavelength interval.

$$\left(\frac{d^2N}{dl\,d\lambda}\right)\propto\frac{1}{\lambda^2} \tag{2.12}$$

The quantum theory of Cerenkov radiation provides more detail, but in accordance with the correspondence principal, yields the classical results for macroscopic phenomena. Since we are concerned only with macroscopic phenomena in this work, we use the classical results. The constant index of refraction subroutine uses these relationships to calculate the amount of Cerenkov radiation produced. Chapter III describes this approach.

III. THE CONSTANT INDEX OF REFRACTION CERENKOV PATCH

Joseph Mack and Thomas Jordan developed a set of sub-routines for the ACCEPT [Ref. 3] computer code which give the code the ability to simulate Cerenkov production. Their modification calculates the number of Cerenkov photons N per unit path length l using the approximation,

$$\frac{dN}{dl} = 2\pi\alpha\left[1 - \frac{1}{\beta^2 n^2}\right]\int_{\lambda_1}^{\lambda_2}\frac{d\lambda}{\lambda^2}, \quad (\lambda_2 > \lambda_1), \tag{3.1}$$

for

$$\frac{dN}{dl} = 2\pi\alpha\int_{\lambda_1}^{\lambda_2}\left[1 - \frac{1}{\beta^2 n^2(\lambda)}\right]\frac{d\lambda}{\lambda^2}, \quad (\lambda_2 > \lambda_1), \tag{3.1a}$$

where α is the fine structure constant. Production is not allowed for $n < \frac{1}{\beta}$.

A. THE CI PATCH

The ACCEPT code transports electrons using multiple-interaction pathlengths. This means that the code simulates the electron path through a material in a series of substeps. At each substep the electron is deflected at an angle which is sampled according to the multiple scattering theory of Gouldsmit and Saunderson. [Ref. 4] Energy losses are determined from the Landau distribution [Ref. 5], knock on electrons are generated, bremsstrahlung photons are produced, etc.

The constant index (CI) subroutine links Cerenkov production to this process. It does this by selecting a uniformly random point along the pathlength at which to generate a Cerenkov photon whose weight represents the expected number of Cerenkov photons produced over the entire pathlength. (See Appendix F for a complete discussion of weight.) The emission polar angle is chosen using the Cerenkov relation, equation (2-1). The azimuthal angle is selected using a uniform random distribution. The mean photon energy of the wavelength band is calculated and assigned to the sampled photon.

Since cross sections are not available for energies as low as those associated with the Cerenkov photons, these photons are not transported as a part of the cascade. Instead, each Cerenkov photon is ray traced through the geometry using geometrical optics and a ray tracing algorithm incorporated into the subroutine. These ray traces depend on the geometry and on a variety of bulk optical properties which are a part of the input file supplied by the user. [Ref. 6] These inputs are:

1. Index of refraction for each zone. This number is the wavelength average index of refraction for each material in the problem.
2. The absorption coefficient (cm^{-1}) is used to calculate absorption losses in each zone.
3. The specular reflection fraction is the fraction of light that undergoes specular reflection at each zone boundary.
4. The diffuse reflection fraction is the fraction of light that undergoes diffuse reflection at each zone boundary.
5. The fractional light transmittance is the fraction of light transmitted through the zone.

B. CERENKOV RAY TRACE

The CI patch works as follows. The user defines the geometry to be used for the problem and enters this as a list of zones in his input file. (See Appendix E) ACCEPT determines the length of a substep for a source electron as it enters the first zone. This is a pathlength value used by ACCEPT to calculate interactions with the material.

If the Cerenkov condition is satisfied, equation (3.1) is used to determine the total Cerenkov weight (Appendix F) produced for this substep. If not, the routine returns control to ACCEPT for the next electron substep. A random position along the electron substep is sampled and used as the starting point for the Cerenkov ray. The Cerenkov angle determined from equation (2.1) and a randomly selected azimuthal angle determine the initial path of the ray.

This ray is traced to the boundary of the next zone. The boundary conditions (the bulk optical properties listed above) are then used to determine whether the ray is diffuse or specularly reflected, completely or partially absorbed, or transmitted into the next zone. The laws of geometrical optics and Snell's law are used to determine the angles of reflection or refraction for the next part of the ray trace.

This process is repeated through each zone until a termination condition is reached. The ray can only terminate in three ways:

1. It gets absorbed.
2. It escapes into the outside universe (the last zone).

3. It is killed because it gets reflected too many times. This parameter (KALTOT) is set by the user in his input file. For the problem under consideration, KALTOT was set to 15. This kill mechanism is included to eliminate the possibility of the ray being reflected a semi-infinite number of times between surfaces (geometric instability).

Tallies are made at each zone to record the Cerenkov weight produced, the energy, the weight absorbed, the weight exiting, and the weight entering the zone. The code also tallies the number of times that production occurs. These tallies are saved for output and of course one of the zones is the detector zone of interest.

This model is quite powerful as a diagnostic tool for analysis of Cerenkov radiation. However, it assumes that the indices of refraction for all materials are constant. In the case of Cerenkov production in a gas such as CO_2 the index of refraction is very nearly constant over the entire range of wavelengths. For example, the index of refraction in CO_2 at 2 atmospheres is 1.00110 at 1800 angstroms [Ref. 7: pp.432-434] while the constant index used in the CI routine is 1.000894. Despite this small difference, calculations using a table of index of refraction by wavelength yield 44 percent more Cerenkov production in the 1800 angstrom bin than predicted by CI. The patches that produce these results are discussed in Chapter IV. A detailed comparison of the results of these patches and the reasons for the differences are discussed in Chapter V.

IV. MODIFICATIONS USING VARIABLE INDICES OF REFRACTION

To produce a code patch that uses the variable indices of refraction for the material producing the Cerenkov radiation and for all the optics through which these photons pass, two different approaches are taken. They are the multiple trace (MT) method and the distribution sampling (DS) method.

A. MULTIPLE TRACE METHOD

The MT method involves splitting the spectrum of Cerenkov photon production into small wavelength bins across which the index of refraction (n) is very nearly constant. The wavelength range is limited to 1800-10000 angstroms. This range is subdivided into 200-angstrom bins from 1800 to 5000 angstroms, where the indices of refraction change rapidly, and in 500-angstrom bins from 5000 to 10000 angstroms, where the indices change slowly. A plot of refractivity ($n - 1$) is shown in Figure 4 on page 13. This shows the index of refraction rising rapidly in the ultraviolet region. However, as the absorption bands are encountered, the index of refraction falls off sharply until the Cerenkov condition is no longer satisfied. The rapid increase in values of refractivity for the wavelengths shorter than 5000 angstroms requires the use of smaller wavelength bins in this region. Wider bins are used for wavelengths above 5000 angstroms to optimize code efficiency.

The number of Cerenkov photons produced in each wavelength bin per pathlength dl is calculated according to equation (3.1). Over a small enough range of wavelengths, the index of refraction is approximately constant and integration of (3.1) over wavelength yields

$$\frac{dN}{dl} = 2\pi\alpha\left(1 - \frac{1}{\beta^2 n^2}\right)\left[\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right], \quad (\lambda_2 > \lambda_1). \tag{4.1}$$

Equation 3.1 must also be integrated over pathlength. For short enough substeps in a homogeneous material this becomes

$$N = 2\pi\alpha l\left(1 - \frac{1}{\beta^2 n^2}\right)\left[\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right], \quad (\lambda_2 > \lambda_1), \tag{4.1a}$$

where l is the length of that particular substep. (In all further equations where $\frac{dN}{dl}$ appears, subsequent integration over pathlength occurs.)

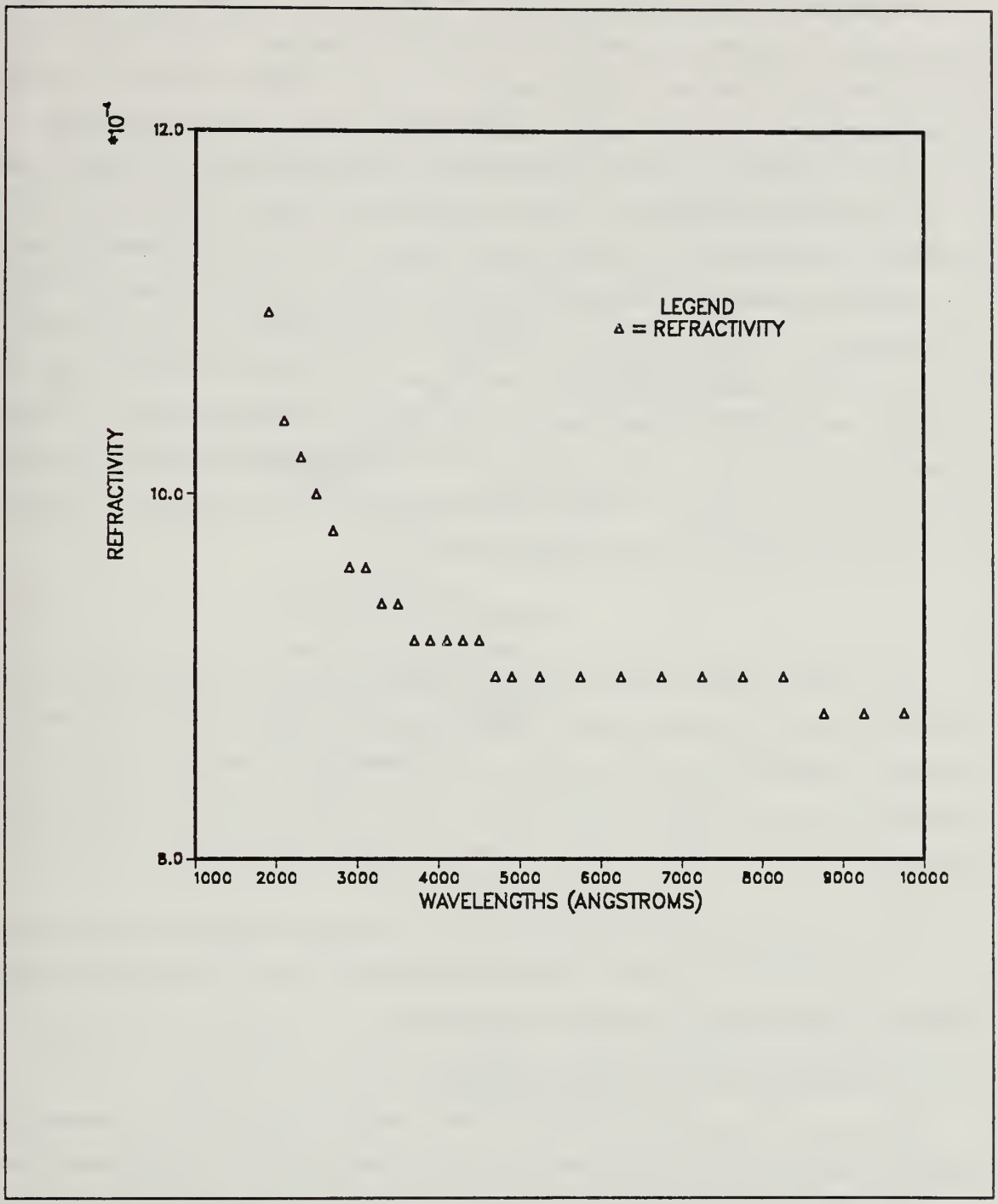

Figure 4. Refractivity by Wavelength: This figure shows the index of refraction values - 1 for CO_2 in the MT and DS methods.

The number of Cerenkov photons per wavelength bin is converted into a weight representative of all photons produced along the entire substep. If the Cerenkov condition is satisfied, a random location along the electron substep is selected. For each wavelength bin, the Cerenkov angle is calculated and all rays of appropriate weight are ray traced through the geometry using the index of refraction for that wavelength and Snell's law in each of the optics. Tallies are made of the Cerenkov weight produced in each zone, the wavelength of the light, and the energy produced. The Cerenkov weight that enters and exits each zone is also recorded, along with the weight that is absorbed. This approach is illustrated in Figure 5 on page 15. This shows two electron substeps. Along each substep, MT samples a position to generate all of the Cerenkov weight for the entire substep. It then calculates the weight in each wavelength bin for the entire substep, determines the Cerenkov angle for each wavelength bin, and ray traces each weight through the geometry. (See the flow diagram for the MT method - Appendix G.) In CO_2 the range of Cerenkov angles when $\beta \approx 1$ is

$$2.4° < \theta < 2.7°. \tag{4.2}$$

The Cerenkov weight produced from a substep is the sum of the weights in each wavelength bin. The total Cerenkov weight produced is then the sum of the weights produced integrating over each substep. If the total of the weights tallied in each wavelength bin were different than the sum of the weights produced on each substep then weight balance would be violated. Clearly, the weight balance for the MT method is correct.

The output from the code patch is listed by wavelength and allows the user to analyze the spectrum of Cerenkov radiation reaching each zone. The update file which implements this method is included as Appendix B.

B. DISTRIBUTION SAMPLING METHOD

While the MT method provides the most detailed approach to examining the Cerenkov radiation produced, its multiple loops cause a large increase in computer time over the CI method. It is obviously a brute force method that forces detailed wavelength coverage. With this in mind, a method which samples the distribution of Cerenkov production was developed. The distribution sampling (DS) method is intended to reduce the amount of computer time required to obtain a similar quality result to that provided by the MT method.

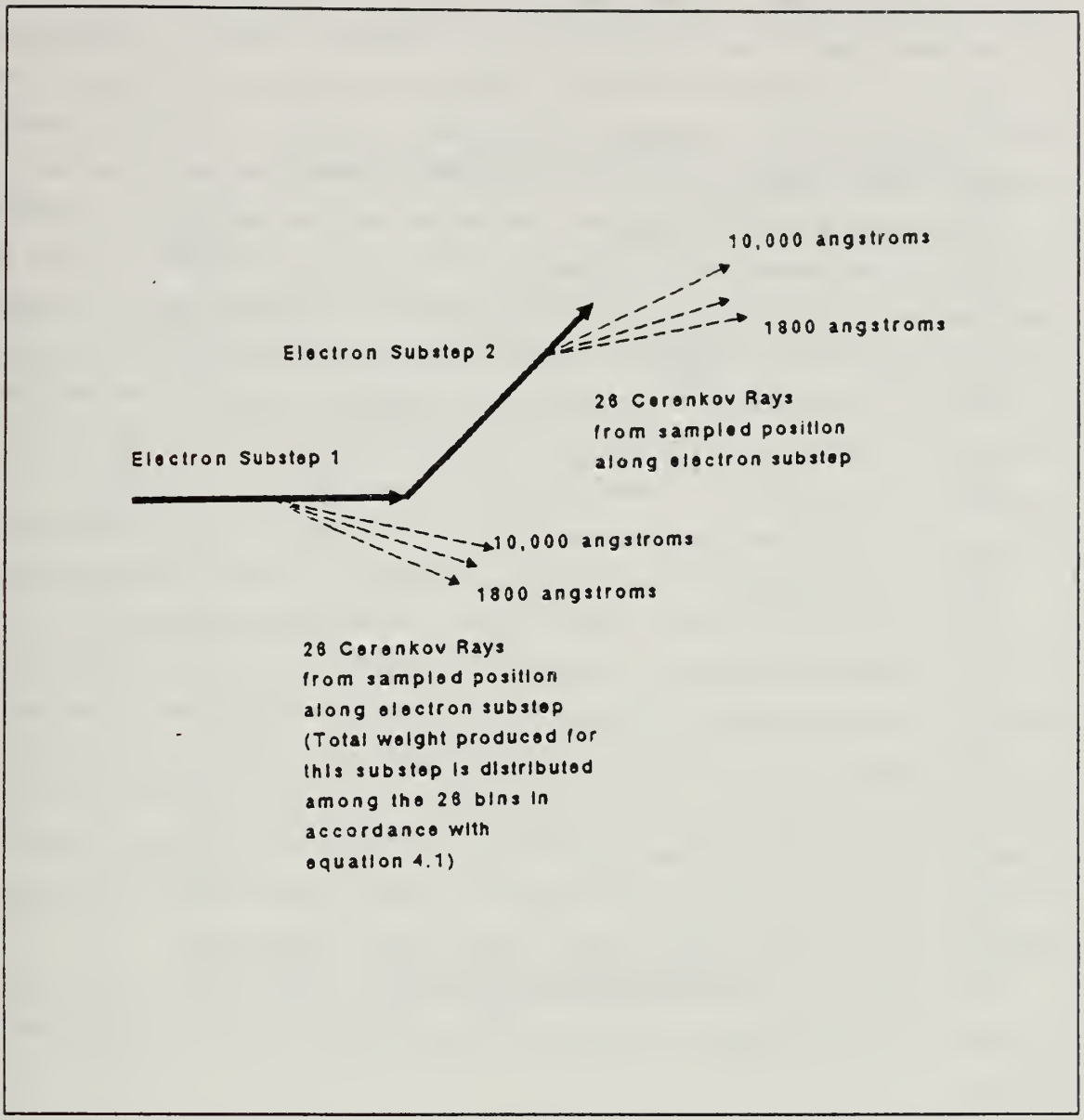

Figure 5. MT Diagram: This figure shows Cerenkov production along 2 electron substeps as calculated by the MT method.

Two additional subroutines are added to the code patch. The first, CKVCDF, creates a discrete cumulative distribution which specifies the probability for Cerenkov production in each wavelength bin. This routine assumes that all Cerenkov production happens in the interval 1800 to 10000 angstroms. The main program calls CKVCDF once, at which time the discrete cumulative distributions for all the materials are calcu-

lated. The program then calculates the expected number of Cerenkov photons produced over the entire range of wavelengths for a given pathlength. The CDF is then sampled through a call to the routine CKVWVL, resulting in one wavelength bin being selected. The total expected weight is assigned to that sampled wavelength. This Cerenkov weight is then ray traced through the geometry making similar tallies as in the MT method.

The number of Cerenkov photons produced in each wavelength bin is unevenly distributed as can be seen from equation (3.1). This is shown in Figure 6 on page 17. Each step on the CDF plot represents the cumulative probability that the sampled photon is in one of the bins from 1800 angstroms up to and including the bin represented by the step. The probability that the photon wavelength is sampled in any particular bin is just the CDF value for that bin less the CDF value for the previous bin. This does not mean that the cutoff for Cerenkov radiation production is 1800 angstroms. This was merely the cutoff wavelength selected based upon available index of refraction data.

More photon production occurs at shorter wavelengths. This calls into question the validity of assigning all of the Cerenkov weight to the sampled wavelength bin. However, this disparity in production is accounted for in the discrete cumulative distribution. While the code may sample a wavelength bin in the longer wavelength region and assign too much weight to it, the probability of sampling this bin is smaller. This will cause a larger sampling frequency at shorter wavelengths. Providing that the distribution is sampled enough times to provide valid statistics, this approach will produce results statistically identical to those of the multiple trace method, while utilizing less computer time.

The subroutine CKVCDF produces the cumulative distribution for each material as follows. The total number of Cerenkov photons produced in each wavelength interval (λ_1, λ_2) ,

$$\frac{dN_i}{dl} \propto 2\pi\alpha\left[\frac{1}{\lambda_i} - \frac{1}{\lambda_{i+1}}\right], \tag{4.3}$$

is calculated for each wavelength bin. These individual values are then summed to yield a normalizing factor (PTOT) such that

$$PTOT = \sum_{i=1}^{26} \frac{dN_i}{dl}, \tag{4.4}$$

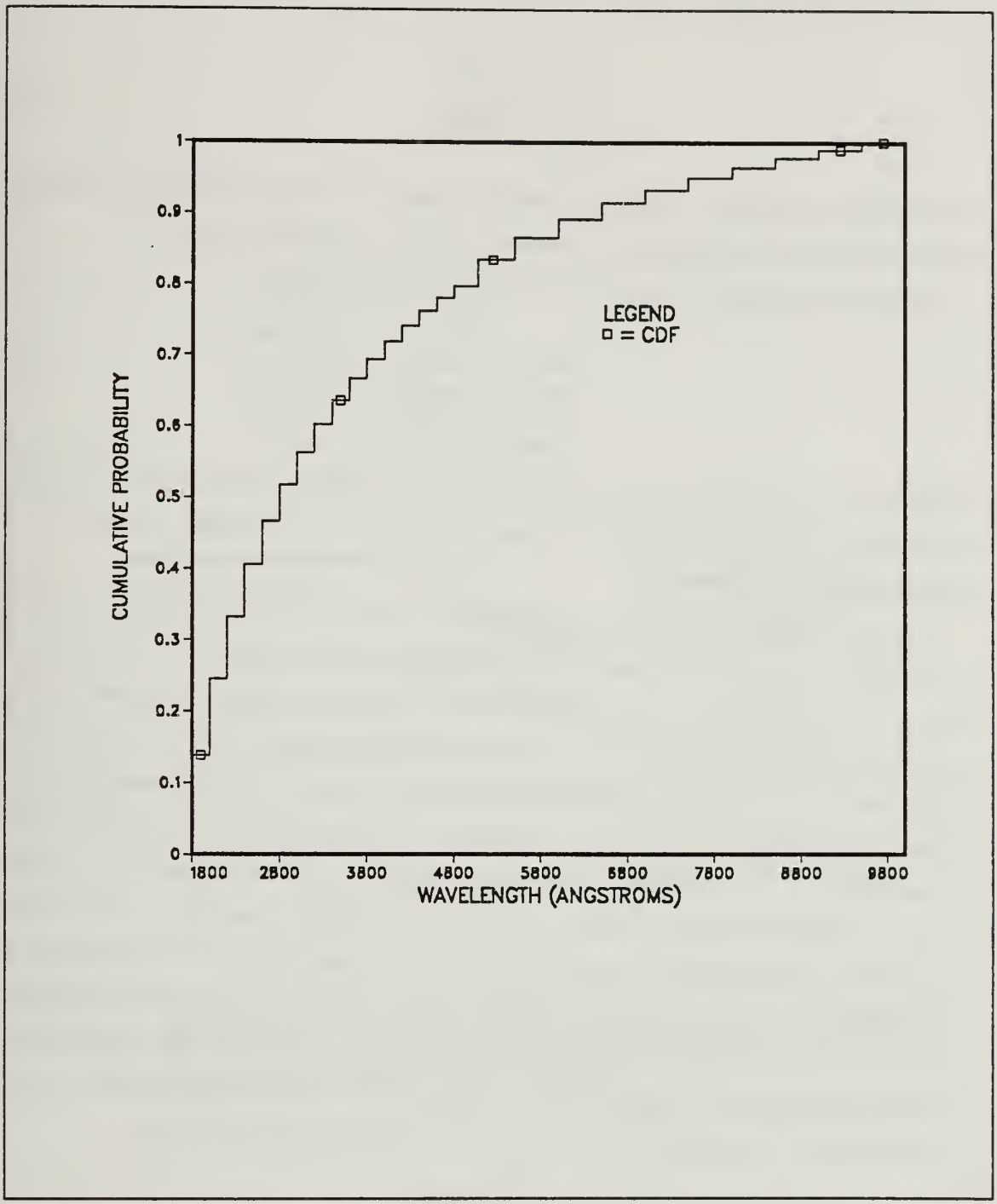

Figure 6. Cerenkov CDF: This figure shows the discrete Cerenkov distribution sampled by the DS method.

where 26 is the number of wavelength bins used.

The discrete probability distribution is then generated by letting

$$P_i = \frac{\left(\frac{dN_i}{dl}\right)}{PTOT}. \tag{4.5}$$

This creates a normalized, discrete probability distribution (the PDF) with P_i representing the probability of generating a Cerenkov photon in wavelength bin (i).

To form the discrete cumulative distribution (CDF), we let

$$CDF(mtrl,i) = \sum_{i=1}^{26} P_i, \tag{4.6}$$

where *mtrl* is the material number and *i* is the index for the wavelength bin. This is put into a loop that creates the CDF for each material and stores these into the two dimensional array CDF(mtrl,i).

This CDF array is randomly sampled (from 0 to 1) to determine which wavelength of Cerenkov light will represent all wavelengths on that specific electron substep. Figure 7 on page 19 shows this process for two electron substeps. A random position is chosen along the substep, all of the Cerenkov weight generated over the substep length for the entire range of wavelengths is assigned to a photon, and the wavelength of the photon is sampled from the discrete cumulative distribution (CDF). The Cerenkov angle is calculated for this wavelength and the photon is ray traced through the geometry. The next electron substep is taken and a new wavelength is sampled. This process is repeated for each substep. (See the flow diagram for the DS method - Appendix H.)

The most important step in justifying the use of distribution sampling is to form a weight balance equation. We must show that the sum of the Cerenkov weights tallied in each wavelength bin equals the sum of the Cerenkov weights produced in each step. In other words we must show that the Cerenkov weight tallied in bin (*i*) is

$$w_i = f_i W, \tag{4.7}$$

where w_i is the weight produced in wavelength bin i and f_i is the fraction of the total weight tallied in bin (*i*). W represents all the Cerenkov weight produced in the problem and is defined by

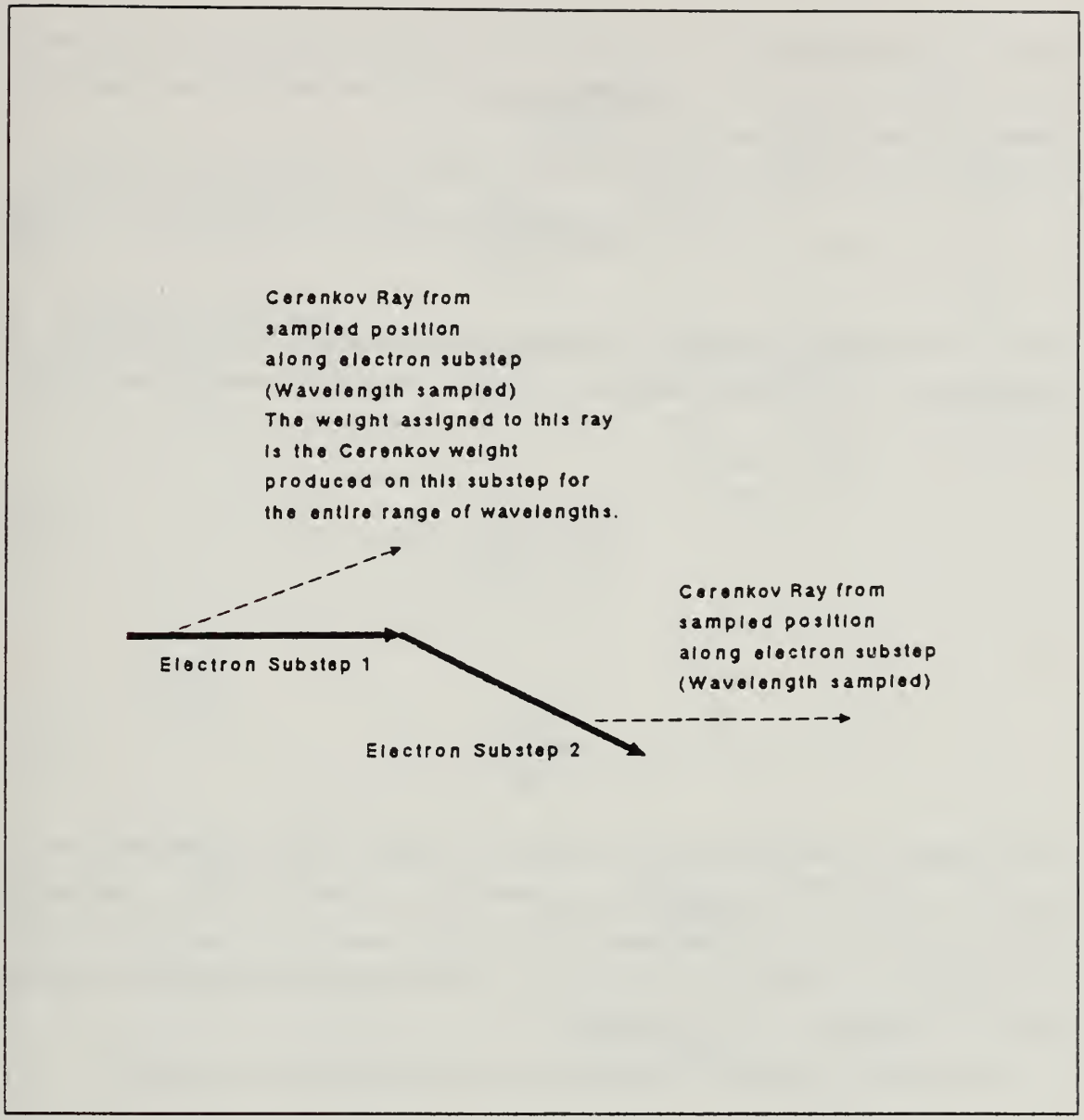

Figure 7. DS Diagram: This figure shows Cerenkov production along 2 electron substeps as calculated by the DS method.

$$W \equiv \sum_{j=1}^{N} \psi_j, \tag{4.8}$$

where N is the total number of electrons substeps on which Cerenkov production occurs and ψ_j is the weight produced on substep j. In the DS method, for a large number of substeps (N) , the weight produced in bin i is

$$w_i \approx P_i \sum_{j=1}^{N} \psi_j \tag{4.9}$$

where P_i is the discrete probability of sampling a wavelength in bin i and is defined by equation (4.5). As the number of substeps on which sampling occurs (N) goes to infinity, we find

$$P_i \sum_{j=1}^{N} \psi_j \approx f_i \sum_{j=1}^{N} \psi_j, \tag{4.10}$$

and

$$w_i \approx f_i \sum_{j=1}^{N} \psi_j. \tag{4.11}$$

Providing that N is sufficiently large to provide the required degree of confidence, we are justified in using the approximation represented by equation (4.11). Substituting equation (4.8) into (4.11) yields equation (4.7). This shows that sampling the distribution provides the required weight balance in each wavelength bin provided that the number of samplings, N, is large enough.[1]

The update file required to implement this routine is included as Appendix C.

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1 An excellent discussion of the estimation of Monte Carlo accuracy is given in the MCNP manual. [Ref. 8: pp. 102-114]

V. RESULTS

Runs were made using the CI, MT, and DS methods to model a gas Cerenkov detector. The geometry for this detector is shown in Figure 8.

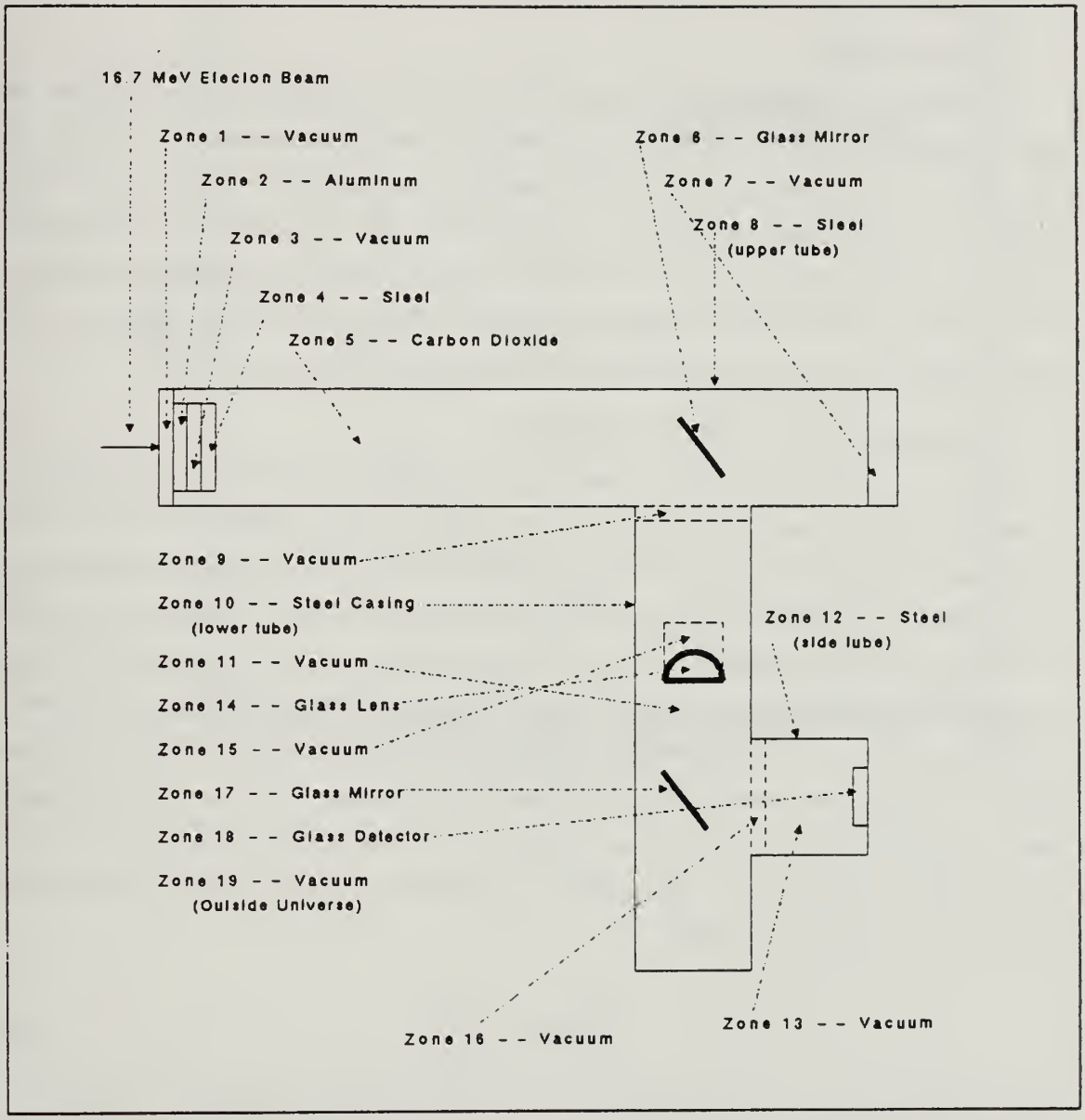

16.7 MeV Electon Beam
Zone 1 - - Vacuum
Zone 2 - - Aluminum
Zone 3 - - Vacuum
Zone 4 - - Steel
Zone 5 - - Carbon Dioxide
Zone 6 - - Glass Mirror
Zone 7 - - Vacuum
Zone 8 - - Steel
(upper tube)
Zone 9 - - Vacuum
Zone 10 - - Steel Casing
(lower tube)
Zone 11 - - Vacuum
Zone 14 - - Glass Lens
Zone 15 - - Vacuum
Zone 17 - - Glass Mirror
Zone 18 - - Glass Detector
Zone 19 - - Vacuum
(Outside Universe)
Zone 12 - - Steel
(side tube)
Zone 16 - - Vacuum
Zone 13 - - Vacuum

Figure 8. Cerenkov Detector Geometry.: This figure shows the geometry for a gas Cerenkov detector that was used to compare the CI, MT, and DS methods.

All of the code patches calculate the total Cerenkov radiation produced in each zone, the amount entering or leaving the zone, and the amount absorbed by the zone. However, the two modified patches also yield data on the wavelengths of radiation in each zone. For a discussion of zones and geometry, see Appendix E.

A. VALIDATION

The first step in comparing the methods was to insure that the code with the new patches produced similar results using the same indicies of refraction. To check this, the variable indicies of refraction in the MT method were replaced with the CI constant indicies. The Cerenkov spectrum, as calculated by the CI and the MT methods, is shown in Figure 9 on page 23. The output of the CI and MT methods are identical. These results verify that the Cerenkov production using the MT method reverts to the constant index (CI) method when the same indicies of refraction are used.

B. COMPARISON OF CODE PATCHES

The first area of interest in comparing the different methods is the amount of Cerenkov radiation produced in zone 5, the CO_2 gas. (See Appendix E for zone descriptions). Figure 10 on page 24 shows a comparison of the production calculated by the constant index and multiple trace routines when the index of refraction is allowed to vary for the MT method. The MT method produces 44 percent more Cerenkov weight in the 1800-angstrom bin than the CI method. (For this problem the index of refraction used for CI in each of the materials was the index for light of 5000 angstroms.) The MT method also shows about 5 percent less production for the long wavelengths than calculated by CI. Figure 11 on page 25 shows the same comparison as a ratio of the amounts calculated by each method. The uncertainties in the the ratio plot are calculated using [Ref. 9: pp. 56-89]

$$\frac{\sigma_r^2}{r^2} \approx \frac{\sigma_x^2}{x^2} + \frac{\sigma_y^2}{y^2}, \tag{5.0}$$

where $r = \frac{x}{y}$ and σ^2 is the variance. The ratio plot emphasizes the differences in the behaviors of the two models. Where the production by the two methods is the same on the graph is where the MT variable index for CO_2 equals the constant index used in CI. This figure illustrates the fact that when the Cerenkov detector photo-multiplier tube

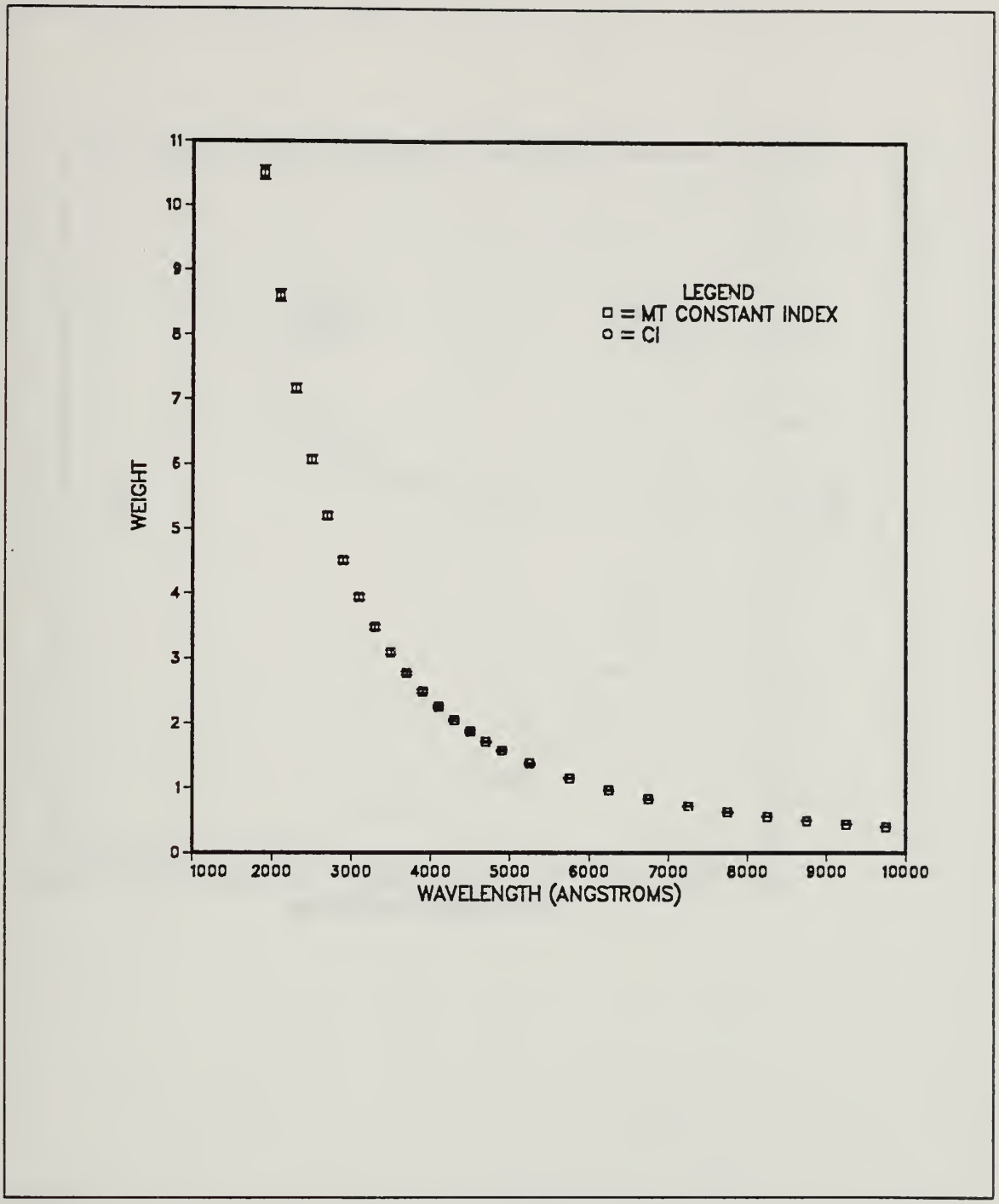


Figure 9. MT vs. CI Cerenkov Weights: This figure shows the Cerenkov weight produced in the CO_2 as calculated by the MT and CI methods when the same indicies of refraction are used.

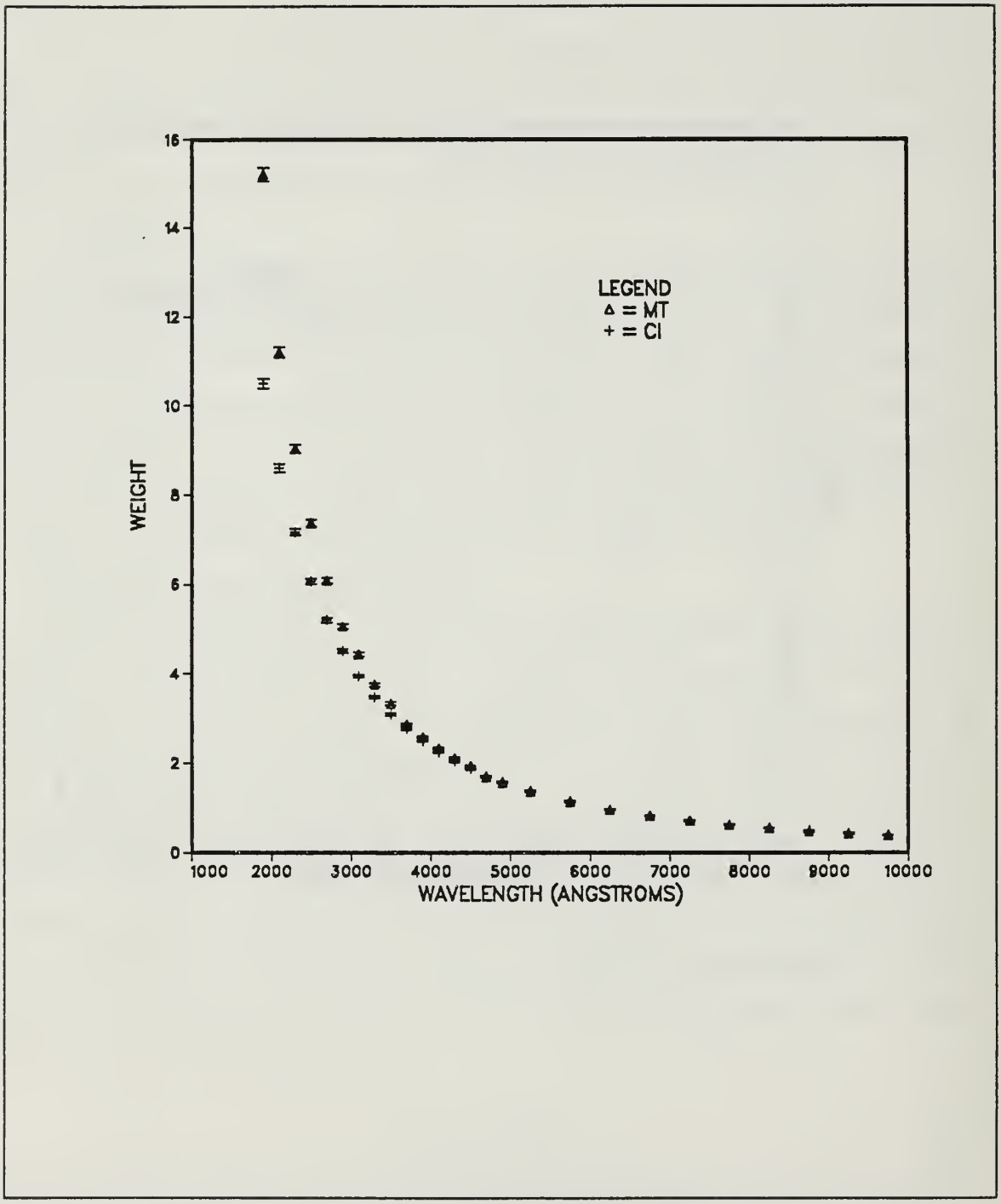


Figure 10. MT vs. CI Cerenkov Weights: This figure shows the Cerenkov weights produced in the CO_2 as calculated by the MT and CI methods.

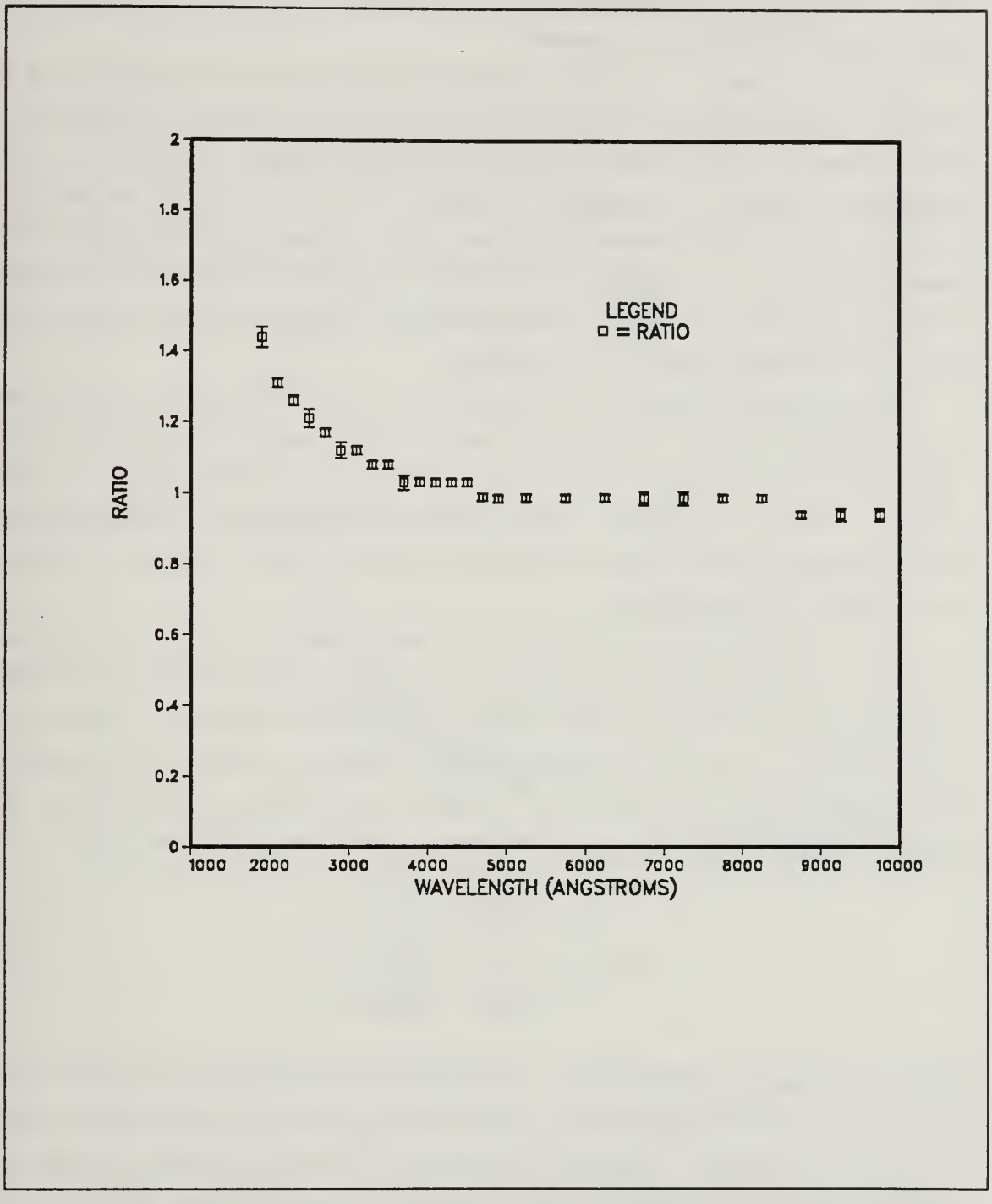


Figure 11. MT vs. CI Production Ratios: This figure shows the ratio of Cerenkov weights produced in CO_2 as calculated by MT to that of CI.

has a non-constant wavelength sensitivity, the inclusion of the proper wavelength dependent index of refraction is important.

Figure 12 on page 27 shows the Cerenkov production calculated by the DS and CI methods. Figure 13 on page 28 shows the ratio comparison of these two methods. The same qualitative result is obtained for the DS and MT methods. This shows the larger production at the short wavelengths and smaller production at the long wavelengths, although there are large statistical variations in the sampling at the wavelengths longer than 5000 angstroms. The degree of the variation depends on the number of batches used in the run or on any biasing techniques applied. Biasing has not been used to improve the statistical accuracy for this problem.

A comparison of the ratio of the distribution sampling (DS) to the multiple trace (MT) calculation, Figure 14 on page 29, shows further evidence of this statistical fluctuation. Figure 14 on page 29 also shows that the results of DS and MT are nearly identical. This is not surprising as the DS method is designed using the same physics, but incorporating a Monte Carlo sampling technique in order to trace fewer Cerenkov rays, thereby improving efficiency.

The next important zone in which to compare the methods is zone 18. This zone represents the photo-multiplier or detector. An analysis of the Cerenkov spectrum here allows the user to see what Cerenkov radiation will arrive at the detector. Figure 15 on page 30 shows a plot of the Cerenkov weights reaching the detector, as calculated by each of the methods. Note that the CI method only calculates a total weight. The fraction, F_i, of the total weight in each wavelength bin is then calculated using

$$F_i = \left[\frac{\left(\frac{1}{\lambda_i} - \frac{1}{\lambda_{i+1}} \right)}{\left(\frac{1}{1800} - \frac{1}{10000} \right)} \right]. \qquad (5.1)$$

Figure 16 on page 31 plots the ratio of the Cerenkov distribution as calculated by the MT method to that calculated by CI. A plot of the ratio of DS to CI weights is shown in Figure 17 on page 32. Again the statistical errors in the DS results are larger than 10 percent for the wavelengths longer than 5000 angstroms, although DS closely matches the MT results.

In order to determine whether the spectrum arriving at the detector is different than that which is produced, it is necessary to examine the ratio of weight that arrives at the detector to weight produced in the CO_2. Figure 18 on page 33 shows this ratio for the

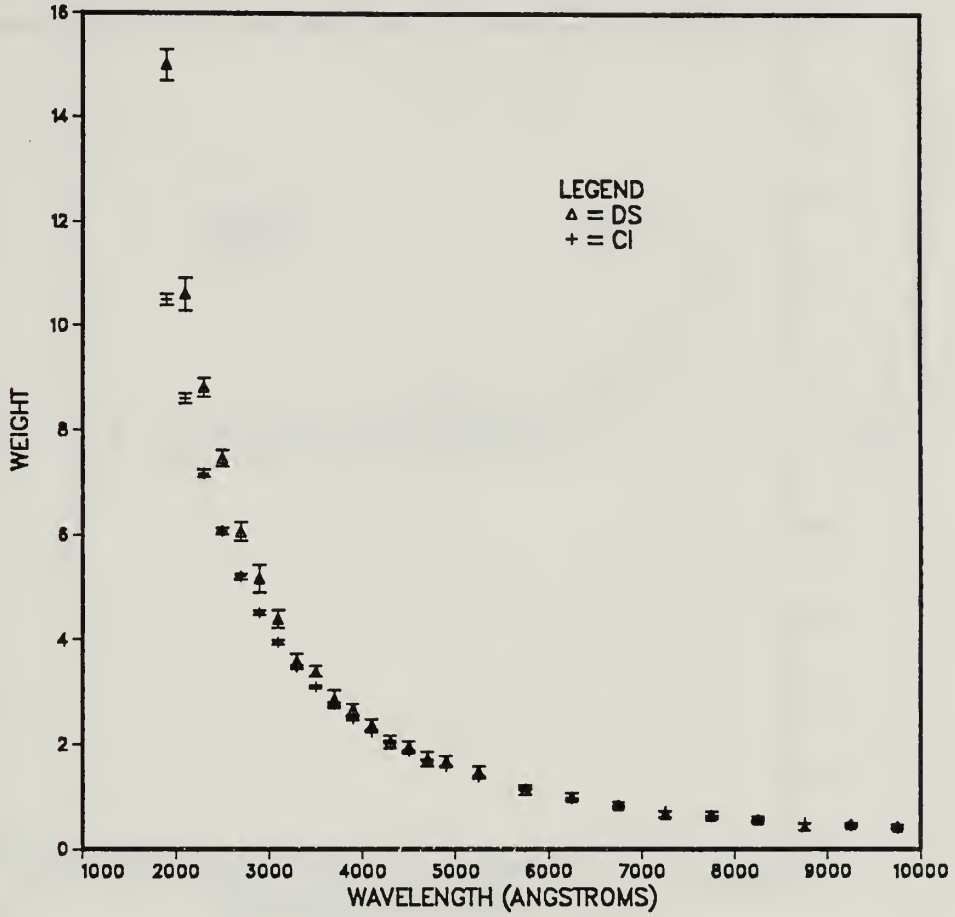


Figure 12. DS vs CI Cerenkov Production: This figure shows the Cerenkov weight produced in CO_2 as calculated by DS and CI.

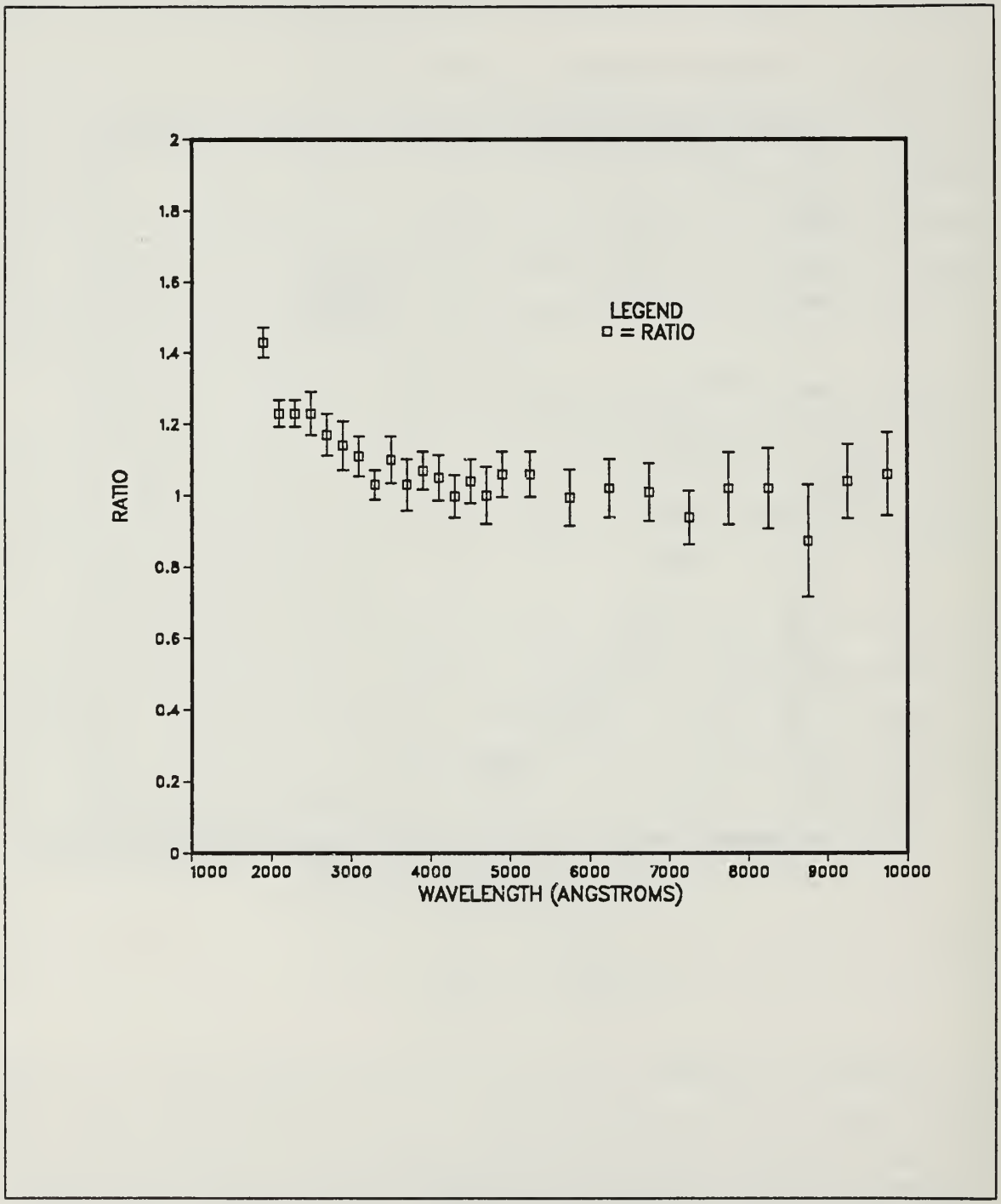


Figure 13. Cerenkov Production Ratio, DS to CI: This figure shows the ratio of the Cerenkov weight produced as calculated by the DS method to that of CI.

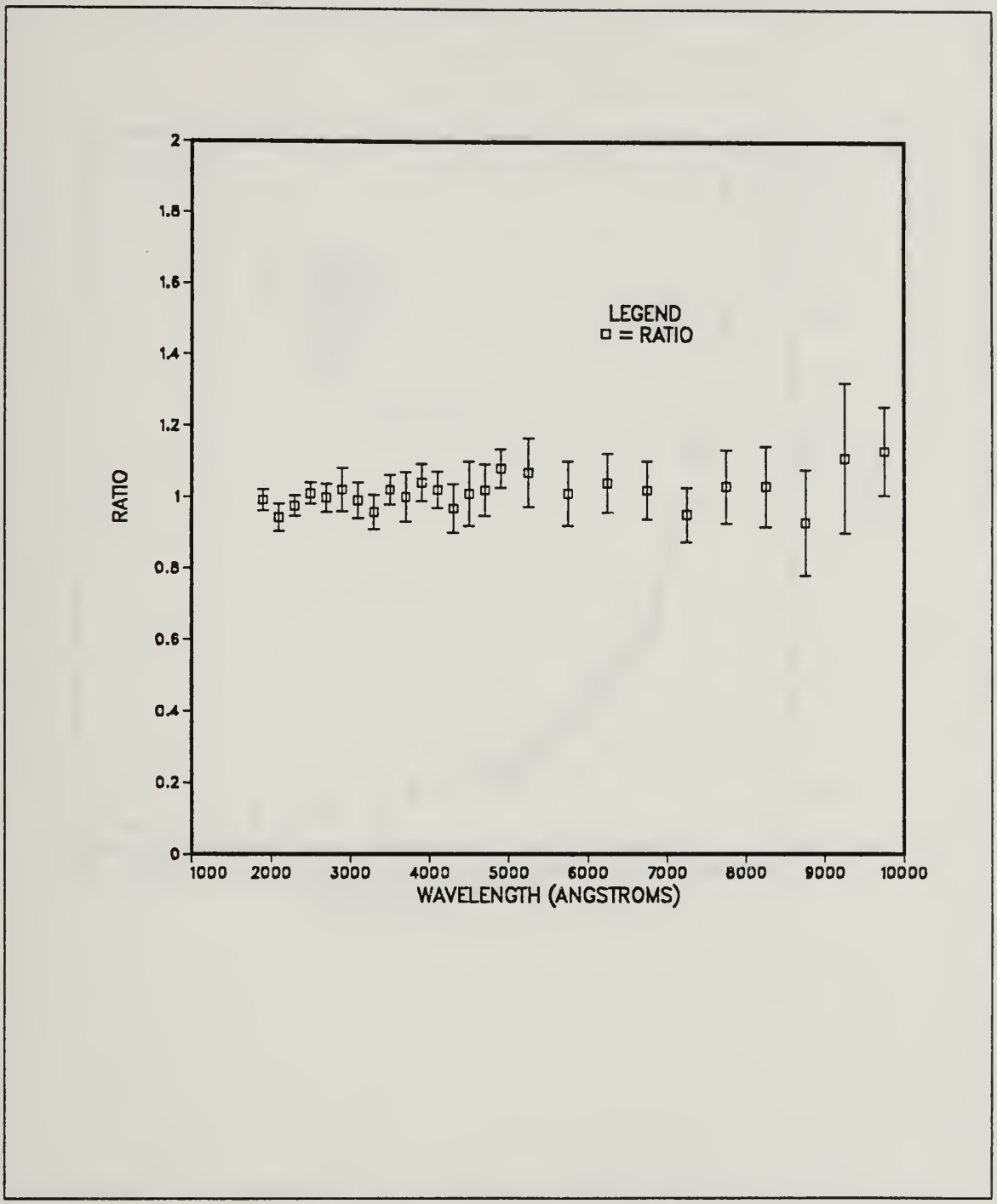


Figure 14. Cerenkov Prodcution Ratio, DS vs. MT: This figure shows the Ratio of the Cerenkov weight produced in the CO_2 as calculated by DS to that calculate by MT.

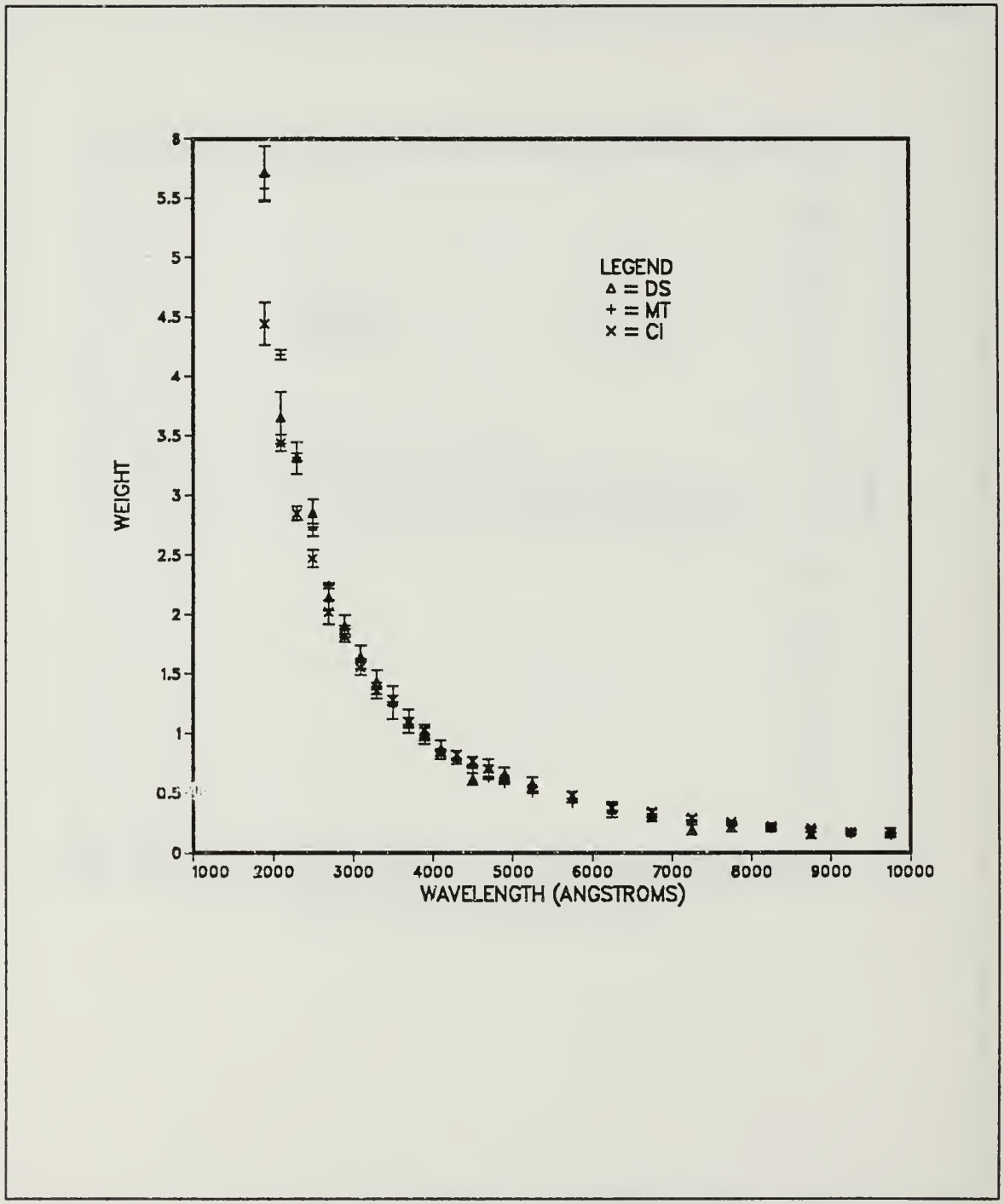


Figure 15. Cerenkov Weights at Detector: This figure shows the Cerenkov weight reaching the detector (zone 18) in each wavelength bin as calculated by the MT, DS, and CI methods.

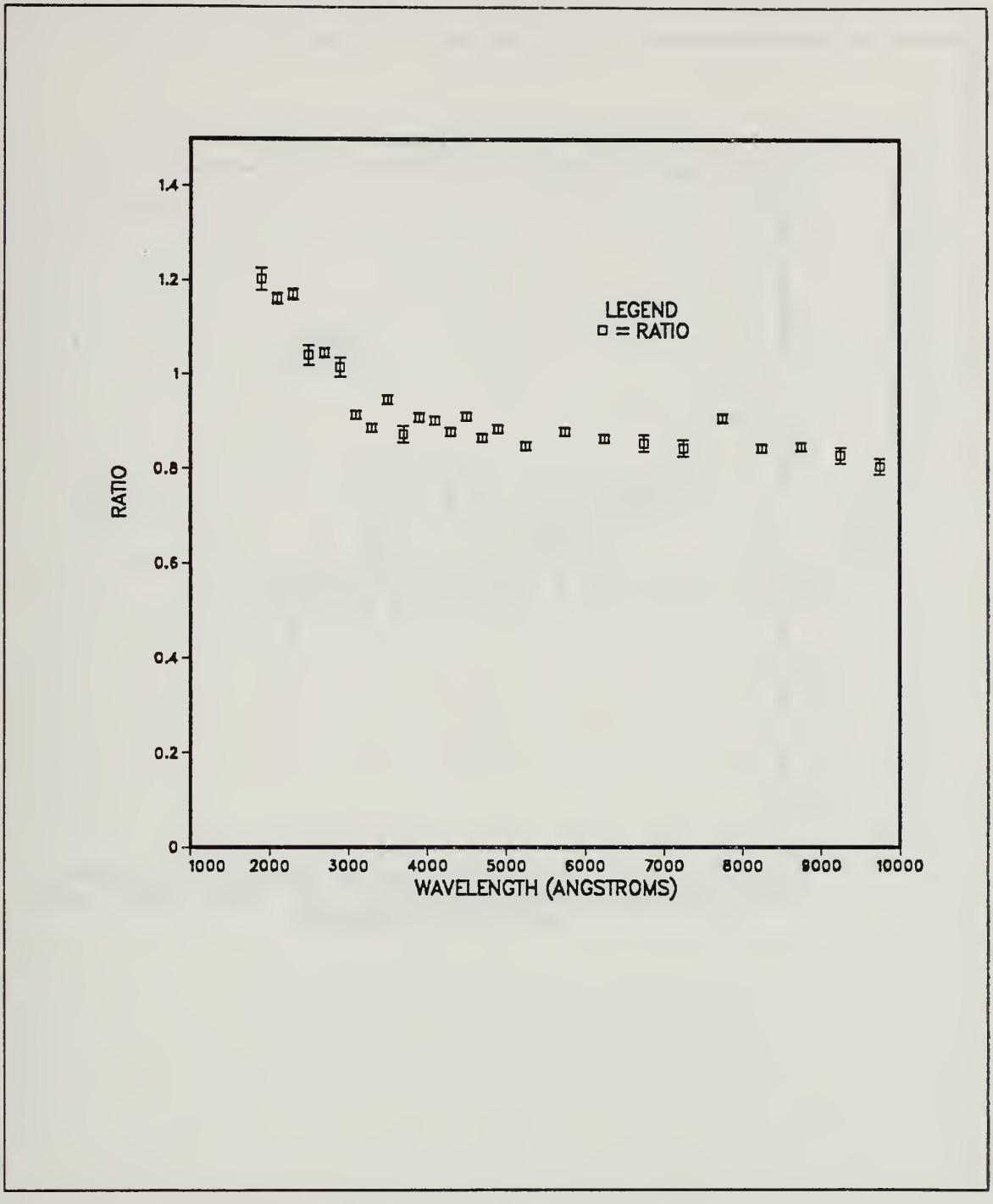


Figure 16. Ratio at Detector, MT to CI: This figure shows a comparison of the Cerenkov spectrum reaching the detector (zone 18) as calculated by MT and CI.

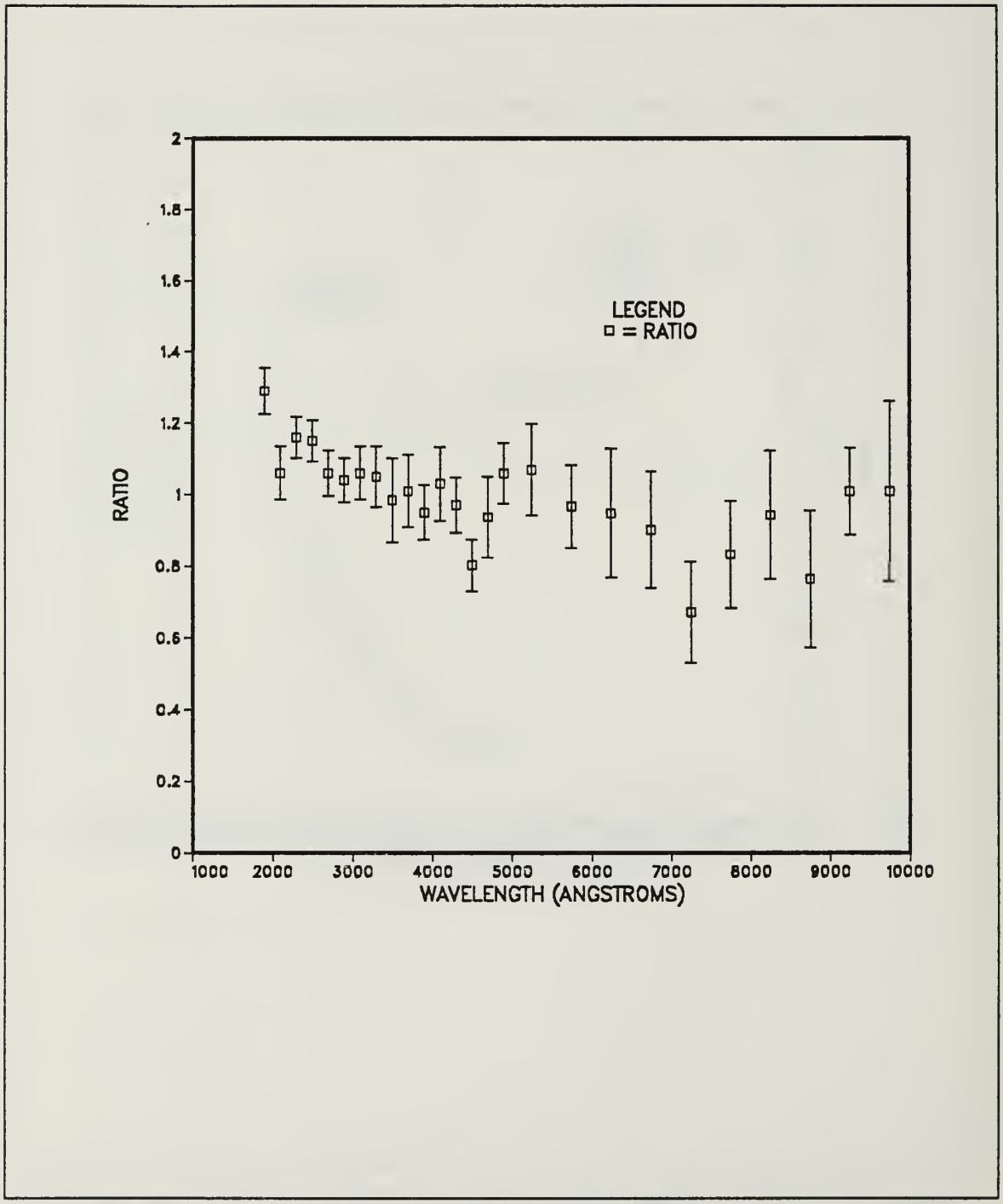


Figure 17. Ratio at Detector, DS to CI: This figure shows the ratio of weights reaching the detector (zone 18) as calculated by DS and CI.

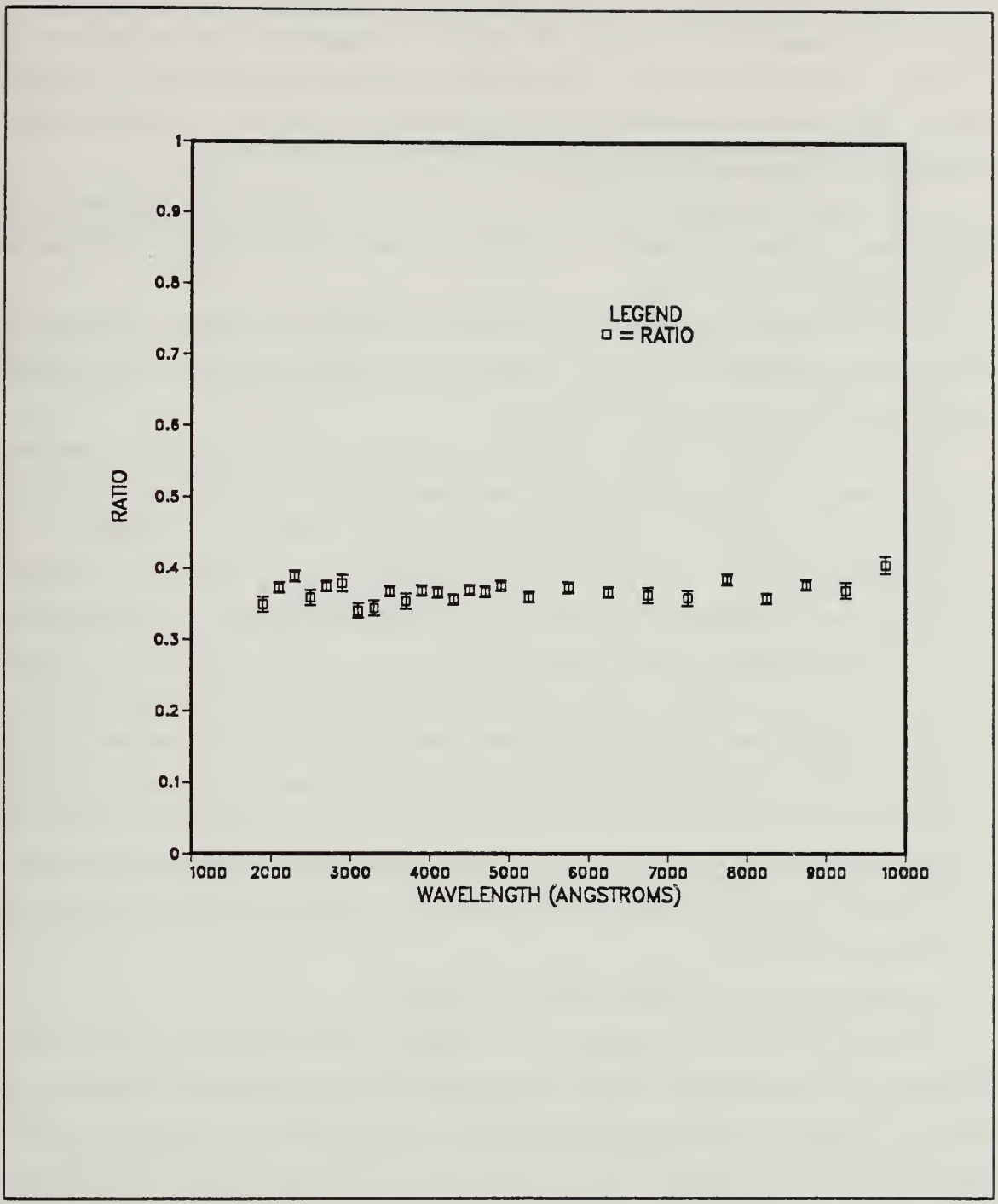


Figure 18. Ratio Reaching Detector, MT Method: This figure shows the ratio of the Cerenkov Weight arriving at the detector to that produced in the CO_2 as calculated by the MT method.

MT method. This plot shows that for this particular Cerenkov detector geometry, the Cerenkov wavelength distribution at the detector is roughly the same as that which is produced, although only about 37 percent of the photons produced make it to the detector. This is because some of the radiation is absorbed in the walls, some is killed from too many reflections, and some escapes.

The ratio of the amount produced to the amount that reaches the detector for the DS method is shown in Figure 19 on page 35. Again only 37 percent of the photons produced arrive at the detector.

The CI method assumes that the distribution arriving at the detector is the same as the original distribution and it shows statistically the same percentage of the original radiation reaching the detector, 35 percent.

Finally, Figure 20 on page 36 provides a zone by zone comparison of the total Cerenkov radiation entering the zone, as calculated by each of the methods. While the geometry of the detector is a complicated set of 19 zones (described in Appendix E), the most important information in this figure is the Cerenkov weight arriving at the detector, Zone 18. Some of the zones show more Cerenkov radiation entering than was produced. This is because reflections may cause Cerenkov rays to enter a zone more than once. The total Cerenkov weight is conserved if the Cerenkov weight produced equals the sum of the weight absorbed, the weight killed due to too many reflections (more than the user specified number of allowed reflections), and the weight that escapes into the outside universe (the last zone, 19). The DS and MT patches both include routines to verify that the weight conservation fraction is unity. Figure 20 on page 36 provides another illustration that the physics used in each of the codes is the same, although the methods of calculation are different.

C. DEPENDENCE ON INDEX OF REFRACTION

The fact that there is 44 percent more Cerenkov radiation produced in the carbon dioxide gas as calculated by MT than that calculated by CI is somewhat surprising. The index of refraction for carbon dioxide gas at 2 atmospheres is 1.00110 for the 1800 angstrom bin. The constant index of refraction used by CI is 1.000894. The maximum difference between indicies of refraction used by the CI routine and the variable index routines amounts to only 0.000206, or 2 parts in 10000.

To understand how such a small change in the index of refraction can produce more than a forty percent increase in the amount of Cerenkov radiation calculated for the shortest wavelengths, it is necessary to analyze the Cerenkov production formula. For

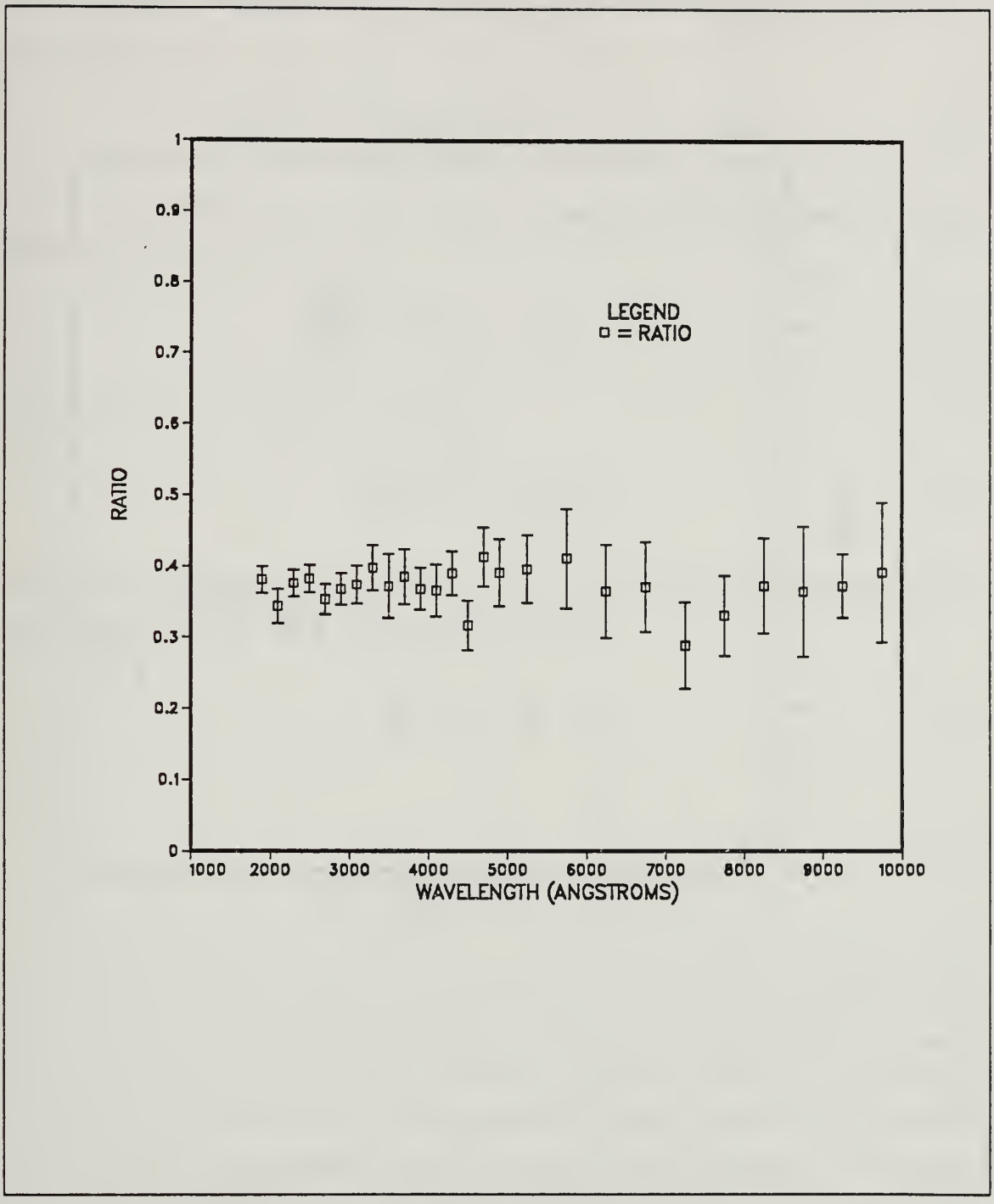


Figure 19. Ratio Reaching Detector, DS Method: This figure shows the ratio of the weight arriving at the detector to that produced as calculated by the DS method.

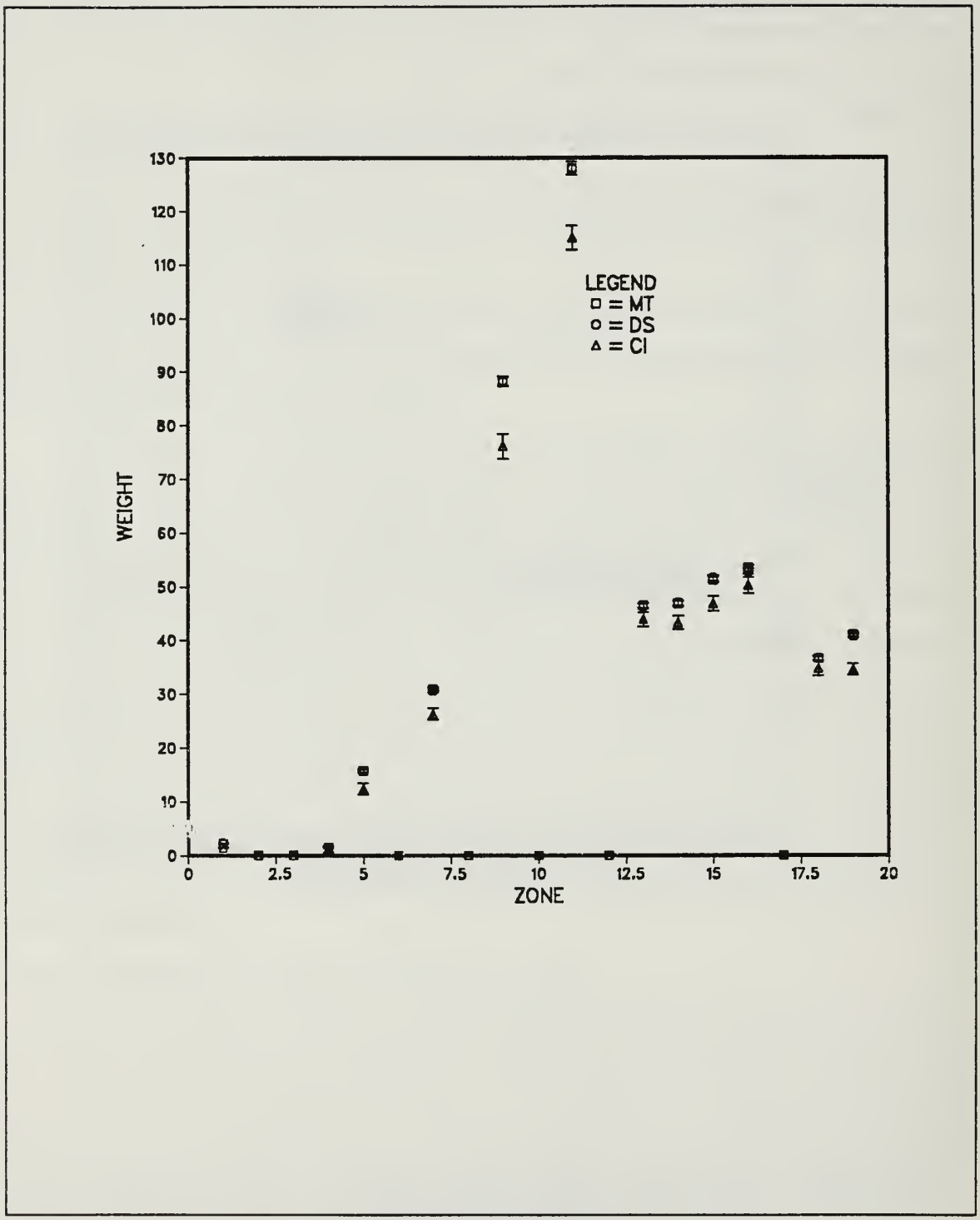


Figure 20. Total Cerenkov Weights Entering Each Zone: This figure shows the total weights calculate by each method.

a small enough wavelength bin and constant n, the number of photons produced per path length is

$$\frac{dN}{dl} = 2\pi\alpha\left(1 - \frac{1}{\beta^2 n^2}\right)\left[\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right], (\lambda_2 > \lambda_1). \tag{5.2}$$

For the extremely relativistic case , $\beta \approx 1$, the number of photons per path length produced in this bin is

$$\frac{dN}{dl} \propto \left(1 - \frac{1}{n^2}\right). \tag{5.3}$$

If we define $n \equiv 1 + \chi$, then this becomes

$$\frac{dN}{dl} \propto \left(1 - \frac{1}{(1+\chi)^2}\right). \tag{5.4}$$

In the case of carbon dioxide gas, $\chi \ll 1$. Therefore, taking the first order Taylor expansion is justified and the above proportionality becomes

$$\frac{dN}{dl} \propto [1 - (1 - 2\chi)], \tag{5.5}$$

or

$$\frac{dN}{dl} \approx 2\pi\alpha(2\chi)\left[\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right]. \tag{5.6}$$

Thus a change from $\chi = 0.000894$ to $\chi = 0.00110$ amounts to a 23 percent increase and it produces a corresponding 23 percent increase in the amount of Cerenkov radiation calculated for the 1800-angstrom bin. Both the MT and DS methods calculated a 44 percent increase in the amount of Cerenkov radiation for this bin. This difference in production is accounted for by the fact that the constant index of refraction used in the CI routine for this problem is below the average index of refraction. The effect of the constant index being below the average index can be removed by normalizing the weights produced in both methods. This is done by dividing the weight in each bin by the total weight calculated for that zone. Figure 21 on page 38 shows that once this normalization is taken into account, the ratio of the Cerenkov weights produced is about 1.23 at 1800 angstroms.

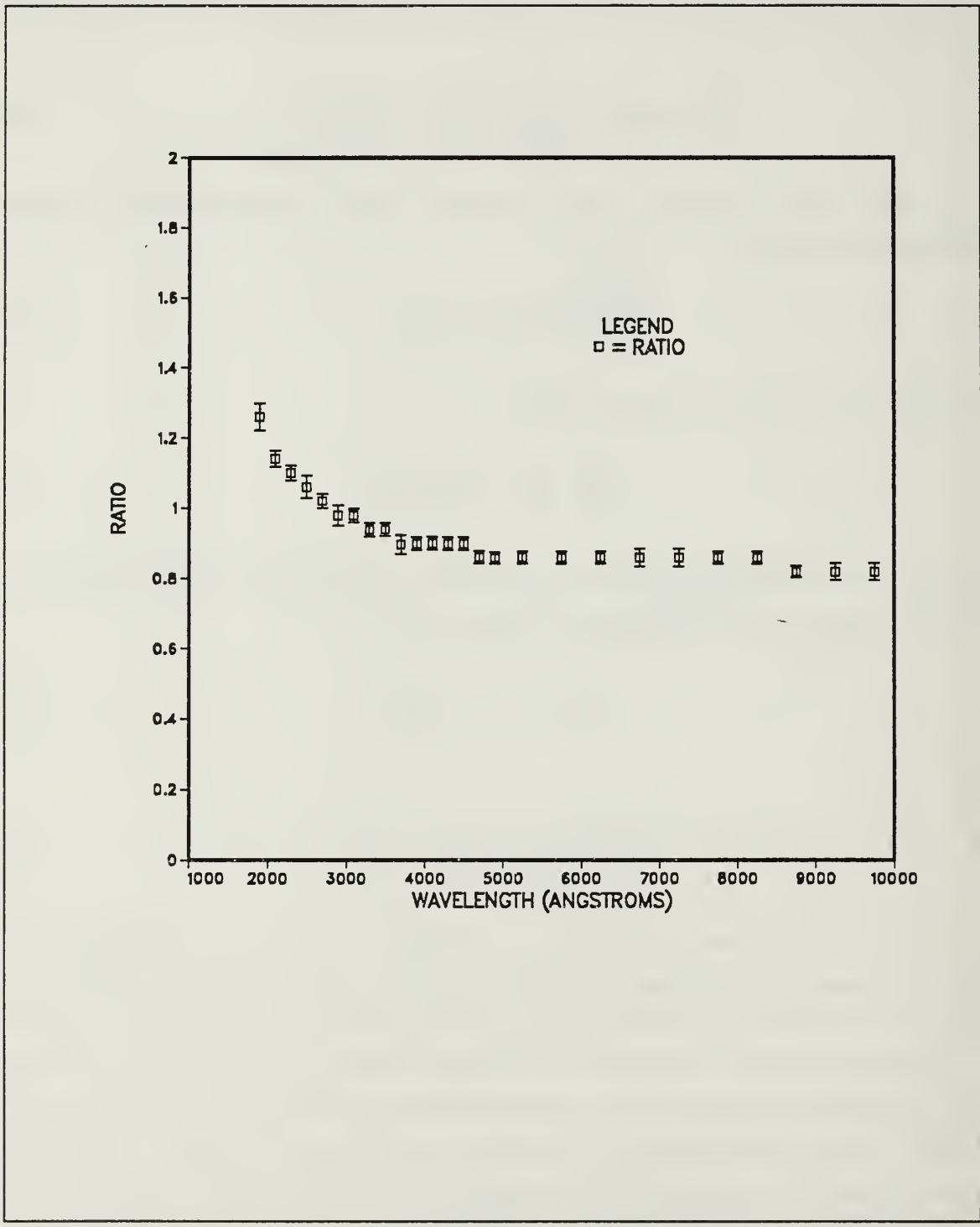


Figure 21. Normalized Cerenkov Production: This figure shows the ratio of the normalized Cerenkov weights produced by MT to that of CI.

Another important characteristic of the parameter χ for gasses is the pressure dependence. χ is proportional to the number density of the molecules in the gas. This can be seen from the dispersion equation,

$$n^2(\omega) = 1 + \frac{Nq_e^2}{\varepsilon_o m_e} \sum_{j=1} \left(\frac{f_j}{\omega_{oj}^2 - \omega^2} \right), \tag{5.7}$$

where n is the index of refraction, ω is the frequency of the light, N is the number of molecules per unit volume in the gas, q_e is the electron charge, m_e is the electron mass, f_j is the number of oscillators in the jth molecule, and ω_{oj} is the resonance frequency of the jth molecule. [Ref. 10: p. 60] Defining the refractivity,

$$\chi \equiv n - 1, \tag{5.8}$$

the first order Taylor expansion of the left hand side of (5.7) is

$$n^2 \approx 1 + 2\chi. \tag{5.9}$$

This approximation is valid for CO_2 since $\chi \ll 1$. Substituting (5.9) into (5.7) yields

$$\chi \propto N, \tag{5.10}$$

the number density of molecules in the gas. For an ideal gas, the relationship between number density and the quantities, pressure and temperature, is specified by

$$N = \frac{P}{RT}, \tag{5.11}$$

where N is the number density, R is the ideal gas constant, and T is the temperature of the gas. [Ref. 11: p. 470] Thus the number density

$$N \propto \frac{P}{T}.$$

This leads to

$$\chi \propto \frac{P}{T}. \tag{5.12}$$

Both of the modified codes utilize this relationship to calculate χ for the gasses. A table of values for indicies of refraction at standard atmospheric pressure and at 293° kelvin are used as a basis for computation. Values for pressure and temperature are read in from the users input file and used to scale χ. This eliminates the need for the user to enter a new table for index of refraction for the gasses every time he desires to investigate the behavior at a different pressure or temperature.

D. SENSITIVITY ANALYSIS

To test the sensitivity of the codes to variation in some of the key parameters, runs were made using different indicies of refraction and different beam energies. A run was made using carbon dioxide at standard atmospheric pressure as opposed to 2 atmospheres, as in the previous runs. At 1 atmosphere of CO_2, the indicies of refraction for CO_2 are below the cutoff for Cerenkov production with the electron beam energy at 16.7 MeV. (The Cerenkov threshold at 1800 angstroms and 1 atmosphere is 14.9 MeV.) This means that ideally there is no production of Cerenkov radiation in the carbon dioxide (zone 5). (Other sources such as transition radiation have not been addressed in this work.) An increase in beam energy again causes $n\beta > 1$ and produces Cerenkov radiation in the CO_2 (zone 5). Note that in Figure 22 on page 41, there is no Cerenkov production in zone 5 for the 16.7 MeV beam while there is for the 17 Mev beam. Both the 16.7 MeV and 17 MeV beams produced about the same amount of Cerenkov radiation as they passed through the glass mirror (zone 6).

Since the indicies of refraction of gasses are dependent upon the pressure of the gas, the modified codes were designed to allow the user to enter the pressures of any air or carbon dioxide in the geometry. The codes then calculate the indicies of refraction for these gasses. The pressure and temperature of the CO_2 and of the air are a part of the regular input file. (Appendix E).

These results show that the output is very sensitive to the indicies of refraction used in the code patch and to the energy of the source particle beam. This is important since it allows the user to vary parameters in the problem and test the results. For example, a user could experiment with different Cerenkov detector designs using different materials and thicknesses for the converter foil, different pressures of CO_2, or try glass or quartz to produce the Cerenkov radiation. He may also be able to select certain regions of the spectrum to emphasize based upon how the Cerenkov light is refracted through his optics.

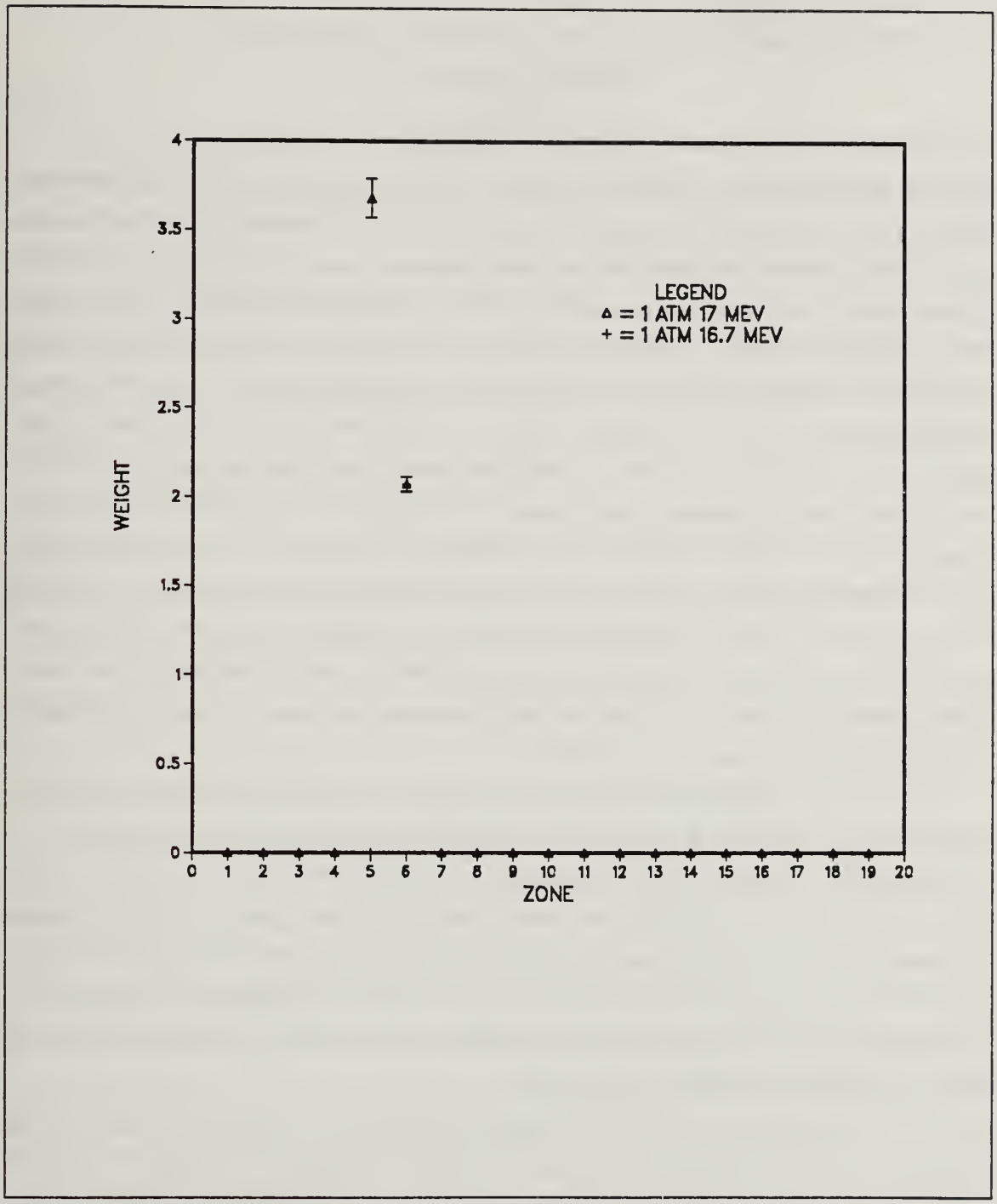


Figure 22. Variations in Pressure and Energy: This figure shows the Cerenkov production in CO_2 at 1 atmosphere by a 16.7 MeV electron beam and by a 17 MeV electron beam.

E. FIGURE OF MERIT

The figure of merit of a Monte Carlo computer model is defined as

$$M = \frac{1}{\sigma t}, \tag{5.13}$$

where σ represents the 1σ relative error and t is the computer run time to achieve the same error. The utility of the figure of merit is that it allows the user to compare the relative efficiencies of different methods used on a computer (the larger the better). The figure of merit was calculated on the IBM 3033 computer. In the detector zone the figure of merit for the MT method was 2.71×10^{-3}. This was uniform across the entire range of wavelengths. The figure of merit for the DS method was 3.37×10^{-3} for wavelengths shorter than 5000 angstroms and was 2.14×10^{-3} for wavelengths of 5000 angstroms and longer. Thus, for wavelengths shorter than 5000 angstroms, the DS figure of merit was 24 percent higher than the MT figure of merit. However, for wavelengths longer than 5000 angstroms, the MT figure of merit was 27 percent higher than the DS figure of merit. This problem with the DS method can be removed by forcing DS to sample the longer wavelengths more often provided that the results of this biasing are removed by a corresponding weight adjustment (the weight assigned to the longer wavelengths would have to be reduced and the weight assigned to shorter wavelengths increased to insure proper weight balance).

While these figures of merit tend to support the idea that the best code for the computer time available is the distribution sampling method, the user should be cautioned that this is only true for wavelengths shorter than 5000 angstroms. The sampling error for the longer wavelengths causes this method to lose value to anyone interested in the entire Cerenkov spectrum from 1800 to 10000 angstroms. However, since this code performs well in the region where the most Cerenkov production takes place, it is a good choice for anyone interested in holding run time down to a minimum while still getting wavelength dependent information.

The CI code patch is the fastest of all the methods but predicts too little Cerenkov production at the shorter wavelengths and too much at the longer wavelengths. It is still valid for the user who is not interested in detailed wavelength dependent information about the Cerenkov spectrum. The MT routine produces the most accurate and detailed results of the three code patches; however, it requires substantial computer time.

VI. CONCLUSIONS

The constant index (CI) Cerenkov routine provides a valuable tool in the design of Cerenkov detectors and for the study of Cerenkov radiation. However, the use of a constant index of refraction in the calculation causes the routine to under-estimate the Cerenkov production at short wavelengths and to over-estimate production at longer wavelengths. For carbon dioxide gas, this produces an error in the CI production weights of -44 percent at 1800 angstroms and +5 percent at 10000 angstroms. These figures are based on trial runs using $n = 1.000894$ as the constant index of refraction in the CI method. Even if a user selects a constant index of refraction so that the total Cerenkov weight produced is the same for CI as for the DS and MT patches, the CI method will under-estimate the Cerenkov production in the 1800-angstrom bin by about 23 percent while over-estimating the production in the 10000-angstrom bin by about 8 percent. This discrepancy is caused by the sensitivity of Cerenkov production to the refractivity $(n - 1)$ of the material in which production occurs.

The CI approach has been modified in the multiple trace (MT) method. MT uses a brute force approach to include wavelength dependence and provides the most detailed treatment of the three code patches. It allows the user to study spectral details not available in the CI method but at a significant cost in computer time.

A compromise, the distribution sampling (DS) method, has also been provided. This approach has a figure of merit that is 25 percent higher than the MT method for wavelengths shorter than 5000 angstroms. However, the figure of merit drops below that of MT for wavelengths longer than 5000 angstroms due to the small number of times these wavelengths are sampled. Since 80 percent of the Cerenkov production occurs below 5000 angstroms, this patch can be used effectively by anyone that does not need information on the entire spectrum. The problem with DS at the longer wavelengths can be removed by biasing the sampling so that all wavelengths are sampled uniformly. However, care must be taken to adjust the weights so that the weight assigned to the longer wavelength bins is reduced while the weight assigned to the shorter wavelength bins is increased in order to maintain proper weight balance.

The MT and DS code patches yield additional detail on the Cerenkov spectrum generated by energetic electrons. Together with the CI routine, the MT and DS modifications to ITS provide the user with an excellent set of tools for use in the study of

Cerenkov radiation and in the design of related diagnostic equipment. There remains the requirement to have a thorough verification against experimental results.

APPENDIX A. ITS (ACCEPT)

ACCEPT is the ITS code for general, combinatorial geometries. This addition of Cerenkov radiation to the ITS code works only with the ACCEPT code.

To run ITS (ACCEPT) the user is required to do the following:

1. Create a compiled version of the code including the subroutine changes to the basic code. This is done by running the UPEML program provided with the ITS package. The input files to this UPEML run are provided as Appendix B and Appendix C.
2. Create a cross section tape by running the program XGEN which is a part of the ITS package. An example input file is provided in Appendix D.
3. Execute the modified ACCEPT program. An example problem input file is also provided in Appendix E along with a description of the combinatorial geometry scheme.

APPENDIX B. MULTIPLE TRACE SUBROUTINE LISTING

```
*IDENT DEFINE
*DEFINE IBM
*DEFINE DOUBLE
*DEFINE ACCEPT
*IDENT,PHILLIPS
*IDENT,PERMT
*D,PARAMS.17
      PARAMETER ( KPTMAX=10000,        INSTAT=100,
*I,HIST.94
      COM = CZERO
*I,HIST.223
        IF((IB .EQ. 1) .AND. (IHIST .LE. 50)) THEN
           IF(IHIST .EQ. 1) WRITE(6,801)
C  SEND ADITIONAL OUTPUT TO OUTPUT UNIT 6
801     FORMAT(1X,1HI,2X,2HLB,7X,1HX,14X,1HY,14X,1HZ,
     1      13X,1HU,13X,1HV,12X,1HW,12X,3HCOM,10X,7HENERGY /)
           WRITE(6,802) IHIST,LB,XB,WT,COM,T
 802       FORMAT(2I3,8(2X,1PE12.5))
C
         ENDIF
C
*IDENT,CKVTR
*I,CALC.78
     6   ,AIRP,CO2,TMPKEL
*I,OUT.30
C  CERENKOV ADDITIONS TO COMMON BLOCK
      COMMON /OUT/
     1   CHER(5,100),CHRNUM(100,100),
     2   CHRWAT(100,100),CHRENG(100,100),CHRABS(100,100),
     3   CHROUT(100,100),CHRENT(100,100),TRNUM(100,100),
     4   TRWAT(100,100),TRENG(100,100),TRABS(100,100),
     5   TROUT(100,100),TRENT(100,100),NRVIR,NCVIR,NAVIR,
     6   CVIRB(11),AVIRB(11),RVIRB(11),VARIND(100,100),WVLNTH(100),
     7   SCOVOL(10,10,10),HVIR,ITRAD,NRBOTH,ICKV,IVIRS,KALTOT,
     8   LBTRAD,NBOTRD,JSRTRD,NCALL,NMBINS,WKILL
*I,INPUT.54
      DIMENSION WVLNT(100),VARIN(100,100)
C*************************************************************************
C******THIS SECTION ASSIGNS VALUES TO THE TABLE OF INDEX OF     ******
C******REFRACTION AND WAVELENGTH.  THE TABLES CREATED ARE       ******
C******STRUCTURED TO COVER WAVELENGTHS IN 200 ANGSTROM BINS     ******
C******FROM 1800 THROUGH 5000 ANGSTROMS, AND IN 500 ANGSTROM    ******
C******BINS FROM 5500 THROUGH 10000 ANGSTROMS.                  ******
C******THE VARIND TABLE CONTAINS INDICES OF REFRACTION FOR      ******
C******EACH MATERIAL.                                           ******
C******                                                        ******
C******VARIND(I,J)          --  INDEX OF REFRACTION FOR MATERIAL******
C******                          MATERIAL I ASSOCIATED WITH    ******
C******                          WAVELENGTH BIN J              ******
C******                                                        ******
C******WVLNTH(J)            --  WAVELENGTH VALUE FOR BIN J    ******
```

```
C******                                                                  ******
C*****************************************************************************
C
C  WAVELENGTHS
      DATA (WVLNT(I),I=1,27)/ 1800,2000,
     1   2200,2400,2600,2800,3000,
     2   3200,3400,3600,3800,4000,
     3   4200,4400,4600,4800,5000,
     4   5500,6000,6500,7000,7500,
     5   8000,8500,9000,9500,10000 /
C  VACUUM
      DATA (VARIN(1,I),I=1,27)/27*1.D0/
C  AIR
      DATA (VARIN(2,I),I=1,27)/
     1  1.00034D0,1.00031D0,1.00030D0,1.00030D0,1.00029D0,
     2  1.00029D0,1.00029D0,1.00029D0,1.00028D0,1.00028D0,
     3  1.00028D0,1.00028D0,1.00028D0,1.00028D0,1.00028D0,
     4  1.00028D0,1.00028D0,1.00028D0,1.00028D0,1.00028D0,
     5  1.00028D0,1.00027D0,1.00027D0,1.00027D0,1.00027D0,
     6  1.00027D0,1.00027D0 /
C  CARBON DIOXIDE (STANDARD ATMOSPHERE)
      DATA (VARIN(3,I),I=1,27)/
     1  1.00055D0,1.00052D0,1.00051D0,1.00050D0,1.00049D0,
     2  1.00048D0,1.00048D0,1.00047D0,1.00047D0,1.00046D0,
     3  1.00046D0,1.00046D0,1.00046D0,1.00046D0,1.00045D0,
     4  1.00045D0,1.00045D0,1.00045D0,1.00045D0,1.00045D0,
     5  1.00045D0,1.00045D0,1.00045D0,1.00044D0,1.00044D0,
     6  1.00044D0,1.00044D0 /
C  GLASS TYPE 458/678(MIL-G-174) (FUSED SILICA DENSITY 2.202 G/CM**3)
      DATA (VARIN(4,I),I=1,27)/
     1  1.58529D0,1.55051D0,1.52845D0,1.51333D0,1.50352D0,
     2  1.49565D0,1.48779D0,1.48274D0,1.47884D0,1.47554D0,
     3  1.47283D0,1.47012D0,1.46830D0,1.46648D0,1.46492D0,
     4  1.46363D0,1.46233D0,1.45991D0,1.45804D0,1.45664D0,
     5  1.45529D0,1.45424D0,1.45332D0,1.45250D0,1.45175D0,
     6  1.45107D0,1.45042D0 /
C  CRYSTAL QUARTZ
      DATA (VARIN(5,I),I=1,27)/
     1  1.66006D0,1.65087D0,1.62626D0,1.61011D0,1.60158D0,
     2  1.59306D0,1.58453D0,1.57600D0,1.56747D0,1.56413D0,
     3  1.56080D0,1.55779D0,1.55554D0,1.55349D0,1.55194D0,
     4  1.55039D0,1.54884D0,1.54616D0,1.54393D0,1.54247D0,
     5  1.54101D0,1.53955D0,1.53839D0,1.53744D0,1.53663D0,
     6  1.53581D0,1.53502D0 /
C
*I,INPUT.436
C  CERENKOV ADDITIONS TO DEFAULT INPUT PARAMETERS
        NMBINS=27
        NCALL=0
        ICKV=0
        IVIRS=0
        ITRAD=0
C  END OF CERENKOV ADDITIONS
*I,INPUT.575
C*************************
```

```
C  CERENKOV
C**************************
          ELSE IF (KOP('CERENKOV') .GE. 0) THEN
             IMATCH = 1
             ICKV = 1
C  SET PRESSURE FOR AIR IN STANDARD ATMOSPHERES
             AIRP = PARM(1)
C  SET PRESSURE FOR CO2 IN STANDARD ATMOSPHERES
             CO2P = PARM(2)
C  SET THE TEMPERATURE IN KELVIN
             TMPKEL = PARM(3)
C  SCALE TEMPERATURE TO 293 DEGREES KELVIN
             TMPKEL = TMPKEL / 293.D0
             DO 93774 I1=1,NMBINS
                VARIND(1,I1)=VARIN(1,I1)
C  INDICES OF REFRACTION - 1 CHANGE PROPORTIONAL TO PRESSURE CHANGE
                VARIND(2,I1)=(VARIN(2,I1)-1.D0)*AIRP/TMPKEL + 1.D0
                VARIND(3,I1)=(VARIN(3,I1)-1.D0)*CO2P/TMPKEL + 1.D0
93774        CONTINUE
             DO 93884 J1=4,20
                DO 93874 I1=1,NMBINS
                   VARIND(J1,I1)=VARIN(J1,I1)
93874           CONTINUE
93884        CONTINUE
             DO 93894 I1=1,NMBINS
                WVLNTH(I1)=WVLNT(I1)
93894        CONTINUE
             KALTOT = PARM(4)
             DO 3034 JJJ=1,NZON
                CALL OPREAD(1,INUNIT,IECHO,IVAL,EOFLAG)
C
C  CHECK INPUT FILE FOR COMPLETE OPTICAL DATA
C
                IF(EOFLAG) THEN
                   WRITE(*,*) 'PREMATURE END OF OPTICAL DATA'
                   STOP
                ENDIF
                IF (KOP('+') .GE. 0) THEN
C
C  ASSIGN VALUES TO CERENKOV INPUT MATERIAL NUMBER FOR ZONE JJJ
                   CHER(1,JJJ) = PARM(1)
C  EXTINCTION COEFFICIENT (1/CM) -- ATTENUATION COEFFICIENT
                   CHER(2,JJJ) = PARM(2)
C  FRACTION OF LIGHT TO BE MIRROR REFLECTED FROM ZONE WALLS
                   CHER(3,JJJ) = PARM(3)
C  FRACTION OF LIGHT TO BE DIFFUSE REFLECTED FROM ZONE WALLS
                   CHER(4,JJJ) = PARM(4)
C  FRACTION OF LIGHT TO BE ACCEPTED FOR ENTRANCE INTO ZONE
                   CHER(5,JJJ) = PARM(5)
C
                ELSE
                   WRITE(*,8903)
8903               FORMAT(1X,'ILLEGAL CKV OR VIRS ZONE DATA')
                   GO TO 9999
                ENDIF
3034            CONTINUE
```

```
C**************************
C  VIRTUAL-SOURCE
C**************************
               ELSE IF (KOP('VIRTUAL-SOURCE') .GE. 0) THEN
                  IMATCH = 1
                  IVIRS = 1
                  HVIR = PARM(1)
                  NRVIR = PARM(2)
                  NCVIR = PARM(3)
                  NAVIR = PARM(4)
                  READ(INUNIT,*,END=9051,ERR=9052)
     1               (RVIRB(IR),IR=1,NRVIR) ,RVIRB(NRVIR + 1)
                  READ(INUNIT,*,END=9051,ERR=9052)
     1               (CVIRB(IC),IC=1,NCVIR),CVIRB(NCVIR + 1)
                  READ(INUNIT,*,END=9051,ERR=9052)(AVIRB(IA),
     1               IA=1,NAVIR) ,AVIRB(NAVIR + 1)
C**************************
C  TRANSITION RADIATION
C**************************
               ELSE IF(KOP('TRANSITION-RADIATION') .GE. 0) THEN
                  IMATCH = 1
                  ITRAD = 1
                  LBTRAD = PARM(1)
                  NBOTRD = PARM(2)
                  JSRTRD = PARM(3)
*I,INPUT.1178
      IF(ICKV .EQ. 1) THEN
C  CERENKOV OPTICAL AND VIRTUAL SOURCE DATA.......
      WRITE(6,9005)
9005  FORMAT(6H  ZONE,6X,6H MTRL ,6X,6HABSORB,6X,6HMIRROR,5X,7HDIFFUSE
     1   ,6X,6HACCEPT,4X,8HTRANSMIT)
      DO 90051 I=1,LZMAX
C  FRACTION OF LIGHT TO BE TRANSMITTED OUT THROUGH ZONE BOUNDARY
         FST = 1 - CHER(3,I) - CHER(4,I)
         WRITE(6,90050)I,(CHER(J,I),J=1,5),FST
90050    FORMAT(I6,1P6E12.4)
90051 CONTINUE
C
      ENDIF
C
      IF(ITRAD .EQ. 1) THEN
         WRITE(6,90311) LBTRAD,NBOTRD,JSRTRD
90311    FORMAT(/' TRANSITION RADIATION LOCATION, ZONE BODY SURFACE'
     1      ,3I6)
C
      ENDIF
C
      IF (IVIRS .EQ. 1) THEN
         WRITE(6,90300) HVIR,NRVIR,NCVIR,NAVIR
90300    FORMAT(/17H VIRTUAL SOURCE Z, E12.4
     1      /' VIRTUAL SOURCE TALLY BINS, RADIAL, POLAR, AZIMUTH,'
     2      , 3I6)
         WRITE(6,9050)(RVIRB(IR),IR=1,NRVIR),RVIRB(NRVIR + 1)
         WRITE(6,9055)(CVIRB(IC),IC=1,NCVIR),CVIRB(NCVIR + 1)
         WRITE(6,9060)(AVIRB(IA),IA=1,NAVIR),AVIRB(NAVIR + 1)
9050     FORMAT(8H RADIAL  ,10E12.4)
```

```
9055      FORMAT(8H POLAR   ,10E12.4)
9060      FORMAT(8H AZIMUTH ,10E12.4)
C
      ENDIF
C
*I,PREP.659
      IF(ICKV .EQ. 1) THEN
         WKILL = CZERO
         DO 241 LLL=1,100
            DO 2401 JJJ=1,100
               CHRNUM(LLL,JJJ) = CZERO
               CHRWAT(LLL,JJJ) = CZERO
               CHRENG(LLL,JJJ) = CZERO
               CHRABS(LLL,JJJ) = CZERO
               CHROUT(LLL,JJJ) = CZERO
               CHRENT(LLL,JJJ) = CZERO
2401        CONTINUE
241      CONTINUE
C
      ENDIF
C
      IF(IVIRS .EQ. 1) THEN
         DO 244 IR=1,NRVIR
            DO 243 IC=1,NCVIR
               DO 242 IA=1,NAVIR
                  SCOVOL(IA,IC,IR) = CZERO
242            CONTINUE
243         CONTINUE
244      CONTINUE
C
      ENDIF
C
*I,OUTPUT.47
      DIMENSION
     1     CHRN(100),CHRW(100),CHRE(100),CHRA(100),CHRO(100),CHRI(100)
      INTEGER ISIGA(100),ISIGB(100),ISIGC(100),ISIGD(100),ISIGE(100),
     1   ISIGF(100),IWVL(100),ISIG1(100) ,ISIG2(100) ,ISIG3(100) ,
     2   ISIG4(100) ,ISIG5(100) ,ISIG6(100)
*I,OUTPUT.561
      IF(ICKV .EQ. 1) THEN
         WTENT = CZERO
         WTABS = CZERO
         WTOT  = CZERO
         WTCON = CZERO
         DO 66 I=1,LZMAX
            DO 56110 J=1,NMBINS-1
               CHRNUM(I,J)=(CHRNUM(I,J)/(CIMAX))
               CHRWAT(I,J)=CHRWAT(I,J)/CIMAX
               CHRENG(I,J)=CHRENG(I,J)/CIMAX
               CHRABS(I,J)=CHRABS(I,J)/CIMAX
               CHROUT(I,J)=CHROUT(I,J)/CIMAX
               CHRENT(I,J)=CHRENT(I,J)/CIMAX
56110       CONTINUE
66       CONTINUE
         DO 10225 I=1,100
            CHRN(I)=CZERO
```

```
            CHRW(I)=CZERO
            CHRE(I)=CZERO
            CHRA(I)=CZERO
            CHRO(I)=CZERO
            CHRI(I)=CZERO
10225     CONTINUE
C  COMPUTE THE TOTALS FOR EACH ZONE
          DO 11230 I=1,LZMAX
             DO 11225 J=1,NMBINS-1
                CHRN(I)=CHRN(I)+CHRNUM(I,J)
                CHRW(I)=CHRW(I)+CHRWAT(I,J)
                CHRE(I)=CHRE(I)+CHRENG(I,J)
                CHRA(I)=CHRA(I)+CHRABS(I,J)
                CHRO(I)=CHRO(I)+CHROUT(I,J)
                CHRI(I)=CHRI(I)+CHRENT(I,J)
11225        CONTINUE
11230     CONTINUE
C
C  WEIGHT CONSERVATION FRACTION = (TOTAL WEIGHT ABSORBED + TOTAL
C  WEIGHT KILLED + WEIGHT THAT ESCAPES) / WEIGHT PRODUCED.
          WKILL = WKILL/CIMAX
          WTENT = CHRI(LZMAX)
          DO 13623 I=1,LZMAX
             WTABS = WTABS + CHRA(I)
             WTOT = WTOT + CHRW(I)
13623     CONTINUE
          WTCON = (WKILL + WTABS + WTENT)/WTOT
       ENDIF
C
       IF (IVIRS .EQ. 1) THEN
          DO 96 IR=1,NRVIR
             DO 86 IC=1,NCVIR
                DO 76 IA=1,NAVIR
                   SCOVOL(IA,IC,IR)=SCOVOL(IA,IC,IR)/CIMAX
76              CONTINUE
86           CONTINUE
96        CONTINUE
C
       ENDIF
C
*I,OUTPUT.1375
       IF(ICKV .EQ. 1) THEN
C**********************CHANGES ADDED HERE**************************
          NPUT=NMBINS-1
          TEMP(1)=WTCON
C  CALCULATE AVERAGES AND STATISTICS FOR TOTALS
          CALL STATS(TEMP,ISIG,1,KPUT)
          WTCON=TEMP(1)
          CALL STATS(CHRN,ISIG1,LZMAX,KPUT)
          CALL STATS(CHRW,ISIG2,LZMAX,KPUT)
          CALL STATS(CHRE,ISIG3,LZMAX,KPUT)
          CALL STATS(CHRA,ISIG4,LZMAX,KPUT)
          CALL STATS(CHRO,ISIG5,LZMAX,KPUT)
          CALL STATS(CHRI,ISIG6,LZMAX,KPUT)
          DO 11220 I=1,LZMAX
```

```
            WRITE(NPRT,9000) I
9000        FORMAT(/,'ZONE =',I3,/,
     1       'WVLNTH',T14,'NUMBER',T22,'STAT',T33,'WEIGHT',T41,'STAT',
     2       T52,'ENERGY',T60,'STAT',T71,'ABSORB',T79,'STAT',T90,
     3       ' LEAVE',T97,'STAT',T108,' ENTER',T115,'STAT',/,
     1       '------',T14,'------',T22,'----',T33,'------',T41,'----',
     2       T52,'------',T60,'----',T71,'------',T79,'----',T90,
     3       '------',T97,'----',T108,'------',T115,'----',/)
C  COMPUTE THE AVERAGES AND THE PERCENT ERROR
            DO 11110 J=1,NMBINS-1
              TEMP(J)=CHRNUM(I,J)
11110       CONTINUE
            CALL STATS(TEMP,ISIGA,NPUT,KPUT)
            DO 11115 J=1,NMBINS-1
              CHRNUM(I,J)=TEMP(J)
11115       CONTINUE
            DO 11120 J=1,NMBINS-1
              TEMP(J)=CHRWAT(I,J)
11120       CONTINUE
            CALL STATS(TEMP,ISIGB,NPUT,KPUT)
            DO 11125 J=1,NMBINS-1
              CHRWAT(I,J)=TEMP(J)
11125       CONTINUE
            DO 11130 J=1,NMBINS-1
              TEMP(J)=CHRENG(I,J)
11130       CONTINUE
            CALL STATS(TEMP,ISIGC,NPUT,KPUT)
            DO 11135 J=1,NMBINS-1
              CHRENG(I,J)=TEMP(J)
11135       CONTINUE
            DO 11140 J=1,NMBINS-1
              TEMP(J)=CHRABS(I,J)
11140       CONTINUE
            CALL STATS(TEMP,ISIGD,NPUT,KPUT)
            DO 11145 J=1,NMBINS-1
              CHRABS(I,J)=TEMP(J)
11145       CONTINUE
            DO 11150 J=1,NMBINS-1
              TEMP(J)=CHROUT(I,J)
11150       CONTINUE
            CALL STATS(TEMP,ISIGE,NPUT,KPUT)
            DO 11155 J=1,NMBINS-1
              CHROUT(I,J)=TEMP(J)
11155       CONTINUE
            DO 11160 J=1,NMBINS-1
              TEMP(J)=CHRENT(I,J)
11160       CONTINUE
            CALL STATS(TEMP,ISIGF,NPUT,KPUT)
            DO 11165 J=1,NMBINS-1
              CHRENT(I,J)=TEMP(J)
11165       CONTINUE
            DO 11170 J=1,17
              IWVL(J)=1600 + J*200
11170       CONTINUE
            DO 11180 J=18,27
```

```
              IWVL(J)=5000 + (J-17)*500
11180         CONTINUE
              DO 11190 J=1,NMBINS-1
                WRITE(NPRT,11181) IWVL(J),CHRNUM(I,J),ISIGA(J),
     1            CHRWAT(I,J),
     2            ISIGB(J),CHRENG(I,J),ISIGC(J),CHRABS(I,J),ISIGD(J),
     3            CHROUT(I,J),ISIGE(J),CHRENT(I,J),ISIGF(J)
11181           FORMAT(I5,T8,1PE12.4,T22,I3,T27,1PE12.4,T41,I3,T46,
     1            1PE12.4,
     2            T60,I3,T65,1PE12.4,T79,I3,T84,1PE12.4,T97,I3,T102,
     3            1PE12.4,T115,I3)
11190         CONTINUE
11220      CONTINUE
           WRITE(NPRT,90055)
90055      FORMAT(/,'TOTALS FOR EACH ZONE',/,
     1       'ZONE',T14,'NUMBER',T22,'STAT',T33,'WEIGHT',T41,'STAT',
     2        T52,'ENERGY',T60,'STAT',T71,'ABSORB',T79,'STAT',T90,
     3        ' LEAVE',T97,'STAT',T108,' ENTER',T115,'STAT',/,
     1        '------',T14,'------',T22,'----',T33,'------',T41,'----',
     2        T52,'------',T60,'----',T71,'------',T79,'----',T90,
     3        '------',T97,'----',T108,'------',T115,'----',/)
           DO 17190 J=1,LZMAX
              WRITE(NPRT,17181) J,CHRN(J),ISIG1(J),
     1           CHRW(J),ISIG2(J) ,
     2           CHRE(J),ISIG3(J) ,CHRA(J),ISIG4(J),
     3           CHRO(J),ISIG5(J), CHRI(J),ISIG6(J)
17181         FORMAT(I5,T8,1PE12.4,T22,I3,T27,1PE12.4,T41,I3,T46,
     1           1PE12.4,
     2           T60,I3,T65,1PE12.4,T79,I3,T84,1PE12.4,T97,I3,T102,
     3           1PE12.4,T115,I3)
17190      CONTINUE
           WRITE(NPRT,11246) WTCON
11246      FORMAT(/,' WEIGHT CONSERVATION FRACTION IS ',E12.4)
        ENDIF
C************************END OF CHANGED OUTPUT************************
90100 FORMAT(I3,3X,6(E12.4,I3))
        IF(IVIRS .EQ. 1) THEN
           WRITE(NPRT,90200)
90200      FORMAT(/'CERENKOV VIRTUAL SOURCE, PHOTONS/SQCM/STR')
           DO 6030 IVR=1,NRVIR
              WRITE(NPRT,90300) RVIRB(IVR),RVIRB(IVR+1)
90300         FORMAT(' R-MIN',E12.4/' R-MAX',E12.4,24X,
     1           ' UPPER AND LOWER POLAR COSINES ')
              DO 6020 LVC=1,NCVIR,5
                 MVC=MIN0(LVC+4,NCVIR)
                 WRITE(NPRT,9040)(CVIRB(IVC),IVC=LVC,MVC)
                 WRITE(NPRT,9050)(CVIRB(IVC+1),IVC=LVC,MVC)
9040             FORMAT(23X,'MINIMUM',5X,'MAXIMUM',6E15.4)
9050             FORMAT(23X,'AZIMUTH',5X,'AZIMUTH',6E15.4)
                 DO 6010 IVA=1,NAVIR
                    L=0
                    DO 6000 IVC=LVC,MVC
                       L=L+1
                       TEMP(L)=SCOVOL(IVA,IVC,IVR)
6000                CONTINUE
                    CALL STATS(TEMP,ISIG,L,KPUT)
```

```
                  WRITE(NPRT,9060)AVIRB(IVA),AVIRB(IVA+1),
     1               (TEMP(IVC),ISIG(IVC),IVC=1,L)
9060              FORMAT(18X,2E12.4,6(E12.2,I3))
6010           CONTINUE
6020        CONTINUE
6030     CONTINUE
C
      ENDIF
C
*I,OUTPUT.1383
      IF(ICKV .EQ. 1) THEN
         WKILL = CZERO
         DO 112 J=1,LZMAX
            DO 111 IJ=1,100
               CHRNUM(J,IJ)=CZERO
               CHRWAT(J,IJ)=CZERO
               CHRENG(J,IJ)=CZERO
               CHRABS(J,IJ)=CZERO
               CHROUT(J,IJ)=CZERO
               CHRENT(J,IJ)=CZERO
 111        CONTINUE
112      CONTINUE
      ENDIF
C
      IF(IVIRS .EQ. 1) THEN
         DO 115 IR=1,NRVIR
            DO 114 IC=1,NCVIR
               DO 113 IA=1,NAVIR
                  SCOVOL(IA,IC,IR)=CZERO
113            CONTINUE
114         CONTINUE
115      CONTINUE
C
      ENDIF
C
*I,INPUT.1853
9051  WRITE(*,9070)
9070  FORMAT
     1   ('0PREMATURE EOF WHILE READING CKV OR VIRS DATA')
      GO TO 9999
9052  WRITE(*,9071)
9071  FORMAT
     1   ('0ILLEGAL DATA IN FIELD WHILE READING CKV OR VIRS DATA')
      GO TO 9999
C
*I,EHIST.522
      IF (ICKV .EQ. 1) THEN
C *** SAVE ZONE INDEX FOR POSSIBLE CALL TO TRANSRAD
         IRSAV = IR
         IRPSAV = IRPRIM
         DISADD=DIST0
         IF(MARK .NE. 1) DISADD=DIST + 1.D-07
         XCHR=X + DISADD*STH(1)*CPH(1)
         YCHR=Y + DISADD*STH(1)*SPH(1)
         ZCHR=Z + DISADD*CTH(1)
         CALL CKVRAD
```

```
     1      (XCHR,YCHR,ZCHR,CTH,STH,CPH,SPH,W,T)
C *** REINSTATE ZONE INDEX FOR POSSIBLE CALL TO TRANSRAD
          IR = IRSAV
          IRPRIM = IRPSAV
          IF(IRPRIM .LT. 0) RETURN
C
      END IF
*I,DISTA.133
      NBOSAV = MA(LSAVE)
*D,PAREM.6
     $  KLOOP,    LOOP,      ITYPE,    NBOSAV
*I,KNOCK.367
C ***************************************************************
C *CERENKOV PRODUCTION SELECTED RANDOMLY ALONG A SUBSTEP*
C ***************************************************************
      SUBROUTINE CKVRAD
     1   (XS,YS,ZS,CPOL,SPOL,CAZI,SAZI,WBETA,EBETA)
C
C  VARIABLE DESCRIPTIONS
C
C  ACCEPT               FRACTION OF CERENKOV RADIATION ACCEPTED INTO
C                          ZONE
C  ALPHA                1./137.0 (FINE STRUCTURE CONSTANT)
C  ANGTCM               1.E-8 (AN ANGSTROM IN CENTIMETERS)
C  C(1)                 X PRESENT DIRECTION COSINE
C  C(2)                 Y PRESENT DIRECTION COSINE
C  C(3)                 Z PRESENT DIRECTION COSINE
C  CAFT
C  CAZI                 COSINE OF AZIMUTHAL SCATTERING ANGLE
C**********CERENKOV INPUTS********
C  CHER(1,J)            MATERIAL NUMBER FOR ZONE J
C                          1 = VACUUM
C                          2 = AIR
C                          3 = CO2
C                          4 = GLASS
C                          5 = QUARTZ
C  CHER(2,J)            EXTINCTION COEFFICIENT (1/CM)
C  CHER(3,J)            FRACTION OF LIGHT TO BE MIRROR REFLECTED
C                          FROM ZONE WALLS
C  CHER(4,J)            FRACTION OF LIGHT TO BE DIFFUSE REFLECTED
C                          FROM ZONE WALLS
C  CHER(5,J)            FRACTION OF LIGHT TO BE ACCEPTED FOR
C                          ENTRANCE INTO ZONE
C******CERENKOV OUTPUTS*******
C
C  CHRNUM(J,K)          NUMBER OF CERENKOV PHOTONS PRODUCED IN ZONE J
C                          FROM WAVELENGTH BIN K
C                          PER INCIDENT SOURCE PARTICLE
C  CHRWAT(J,K)          CERENKOV WEIGHT PRODUCED IN ZONE J
C                          FROM WAVELENGTH BIN K PER INCIDENT
C                          SOURCE PARTICE WEIGHT OF 1.0
C  CHRENG(J,K)          CERENKOV ENERGY PRODUCED IN ZONE J
C                          FROM WAVELENGTH BIN K PER INCIDENT
C                          SOURCE PARTICLE
C                          = CHRENG(I) + EP*WP
C  CHRABS(J,K)          CERENKOV WEIGHT ABSORBED (KILLED) IN ZONE J
```

```
C                              FROM WAVELENGTH BIN K PER
C                              INCIDENT SOURCE PARTICLE
C                              = CHRABS(J) + WNEW  OR WABS
C  CHROUT(J,K)              CERENKOV WEIGHT THAT EXITS ZONE J
C                              FROM WAVELENGTH BIN K PER
C                              INCIDENT SOURCE PARTICLE
C                              = CHROUT(J) + WP
C  CHRENT(J,K)              CERENKOV WEIGHT THAT ENTERS ZONE (J+1)
C                              FROM WAVELENGTH BIN K PER
C                              INCIDENT SOURCE PARTICLE
C                              = CHRENT(J+1) + WP
C*******************************
C  CN(J)                    NORMAL FROM THIS REGION TOWARDS NEXT REGION
C  CP(J)                    DIRECTION COSINES IN MOVING FRAME
C  CP2                      COSINE SQUARED
C  POL                      COSINE OF POLAR SCATTERING ANGLE
C  CPRE                     SUM OF SQUARES OF CURRENT DIRECTION COSINES
C  CPRO                     PRODUCTION COSINE IN THE MOVING FRAME
C  CRAT                     RATIO OF COSINES
C  CSQ                      SQUARE ROOT OF SUM OF SQUARES OF X AND Y DIRECTION
C                              COSINES
C  CX                       X DIRECTION COSINE
C  CZ                       Z DIRECTION COSINE
C  DIFFU                    PROBABILITY FOR DIFFUSE REFLECTION
C  EBETA                    ELECTRON ENERGY
C  EE                       GAMMA SQUARED
C  EP                       ENERGY OF CERENKOV PHOTON
C  FST                      FRACTION OF LIGHT TO BE TRANSMITTED OUT
C                              THROUGH ZONE BOUNDARY
C                              = 1.0 - CHER(3,J) - CHER(4,J)
C  IBFIND                   FUNCTION TO FIND NEXT ZONE
C  J                        COUNTER
C  KALTOT                   MAXIMUM NUMBER OF ALLOWED REFLECTIONS
C  KLIDE                    COUNTER FOR NUMBER OF REFLECTIONS
C  NR                       PRESENT USER REGION
C  NRC                      PRESENT CODE REGION
C  NRPC                     NEXT CODE REGION
C  NRMAX                    MAX ZONE NUMBER
C  NZON                     ZONE NUMBER
C  PI                       3.14159
C  PLANKC                   1.2405E-10
C  RA                       RANDOM NUMBER
C  RANF(ARG)                RANDOM NUMBER PRODUCING FUNCTION
C                              ARG = 0    PRODUCES UNIFORM RANDOM NUMBER
C  RVIR                     VIRTUAL SOURCE RADIUS
C  SAFT
C  SAZI                     SINE OF AZIMUTHAL SCATTERING ANGLE
C  SCOVOL(J,J,J)            DATA FOR VIRTUAL SOURCE
C                             RADIUS AND TWO ANGLES
C  SHD                      LENGTH OF ELECTRON SUBSTEP IN CENTIMETERS
C  SIG                      PRODUCTION OF CERENKOV PHOTONS PER CM PER MEV
C  SPECU                    PROBABILITY FOR SPECULAR REFLECTION
C  SPOL                     SINE OF POLAR SCATTERING ANGLE
C  ST                       DISTANCE TO BOUNDARY
C  STP                      SAMPLED FRACTION OF ELECTRON SUBSTEP IN CM
C  V                        RATIO OF ELECTON VELOCITY TO SPEED OF LIGHT (BETA)
```

```
C  V2                    BETA SQUARED
C  V2N2                  BETA SQUARED TIMES INDEX OF REFRACTION SQUARED
C  VARIND(I,J)           INDEX OF REFRACTION FOR MATERIAL I AND WAVELENGTH
C                        BIN J
C  VOLVIR                VOLUME FOR VIRTUAL SOURCE
C  WABS                  CERENKOV WEIGHT ABSORBED IN ZONE
C  WVLNTH(I)             WAVELENGTH BIN I
C                        THESE BINS RUN FROM 1800 TO 5000 ANGSTROMS
C                        IN 200 ANGSTROM WIDE BINS AND THEN FROM
C                        5500 TO 10000 ANGSTROMS IN 500 ANGSTROM BINS
C  WBETA                 ELECTRON WEIGHT
C  WNEW                  REDUCED WEIGHT OF CERENKOV PHOTON
C  WP                    WEIGHT OF CERENKOV PHOTON
C  WT(J)                 TEMPORARY POSITION ARRAY
C  WZERO                 INITIAL WEIGHT OF CERENKOV PHOTON
C  XB(J)                 TEMPORARY POSITION ARRAY
C  XCHR(J)               PRESENT POSITION
C  XPI(J)                POSITION AT BOUNDARY JUST INSIDE THIS REGION
C  XPO(J)                POSITION AT BOUNDARY JUST INSIDE NEXT REGION
C  XREF                  INDEX OF REFRACTION
C  XS                    CURRENT X POSITION (INPUT IN PARAMETER LIST)
C  XVIR                  VIRTUAL SOURCE X POSITION
C  YREF                  INDEX OF REFRACTION FOR NEXT ZONE
C  YS                    CURRENT Y POSITION (INPUT IN PARAMETER LIST)
C  YVIR                  VIRTUAL SOURCE Y POSITION
C  ZE                    CHARGE ON SOURCE PARTICLE IN ELECTRON VOLTS
C  ZS                    CURRENT Z POSITION (INPUT
C                           IN PARAMETER LIST)
C**********************************************************************
C
*CA CNSTNT
*CA PARAMS
*CA OUT
*CA CALC
*CA PAREM
*CA STTS
*CA GOMLOC
*CA DBG
*CA ORGI
*CA COG
*CA SECZN
      DOUBLE PRECISION DSEED, IRAN
      COMMON /VAXRAN/ IRAN
      DIMENSION C(3),CN(3),CP(3),XCHR(3),XPI(3),XPO(3)
      DIMENSION XCHR1(3),XB1(3),WT1(3)
      DIMENSION WP(100)
      DATA PLANKC,ANGTCM/1.2405D-10,1.D-8/
C     RANDOM NUMBER STATEMENT FUNCTION FOR IBM
      RANF(DSEED)= GGUBFS(DSEED)
      NCALL = NCALL + 1
      ALPHA = 1.D0/137.D0
      PI=DACOS(-1.D0)
      TIME=1.D0
      M=1
C  CALCULATE DIRECTION COSINES FOR SOURCE PARTICLE
      C(1) = SPOL*CAZI
```

```
      C(2) = SPOL*SAZI
      C(3) = CPOL
C  SAMPLE RANDOM LOCATION FOR CERENKOV PRODUCTION ALONG A SUBSTEP
      STP = SHD*RANF(IRAN)
C  SET ELECTON LOCATION
      XCHR(1) = XS
      XCHR(2) = YS
      XCHR(3) = ZS
C  PRESENT ZONE OF ELECTRON
      NRC = LBCZ
      NR = IROR(NRC)
      NRMAX = NZON
C  UPDATE RANDOMLY SAMPLED PRODUCTION POSITION
      DO 100 J=1,3
         WT(J) = C(J)
         XB(J) = XCHR(J) + C(J)*(STP - SHD)
         XCHR(J) = XB(J)
C  SAVE VALUES TO INITIALIZE MAIN LOOP
         WT1(J) = WT(J)
         XB1(J) = XB(J)
         XCHR1(J) = XCHR(J)
100   CONTINUE
C  FIND ZONE OF PRODUCTION POSITION AND COMPUTE UNCOLLIDED
C     ESCAPE DISTANCE.
      CALL ZONEA
C
C  NEXT ZONE TO BE ENTERED. IRPRIM AND IR SET BY SUBROUTINE ZONEA
      NRC=IRPRIM
C  PRESENT ZONE OF PRODUCTION
      NR=IR
C  SAVE ZONE TO INITIALIZE MAIN LOOP
      NRC1 = NRC
      NR1 = NR
C  INITIALIZE XREF TO MINIMUM VALUE
      MTRL=IDINT(CHER(1,NR))
      XREF=VARIND(MTRL,27)
      NTYPE=1
C *** CALCULATE VELOCITY OF SOURCE PARTICLE ***
C  ELECTRON ENERGY NORMALIZED TO REST MASS ENERGY
C     TOTAL ENERGY = KINETIC ENERGY + REST MASS ENERGY
      EE = 1.D0 + EBETA/.511D0
C  NORMALIZED VELOCITY (V2 = BETA SQUARED)
      V2 = 1.D0 - 1.D0/(EE*EE)
C  (V = BETA)
      V = DSQRT(V2)
C  (BETA SQUARED * INDEX OF REFRACTION SQUARED)
      V2N2 = V2*XREF*XREF
C *** DOES PARTICLE MEET CERENKOV THRESHOLD ***
      IF(XREF .LE. 1.D0) GO TO 1600
      IF(V2N2 .LE. 1.D0) GO TO 1600
C  THE CERENKOV PHOTON WEIGHT TO BE USED IS THE
C  WEIGHT OVER THE RANGE OF WAVELENGTHS FOR THAT BIN AND FOR THE
C  ENTIRE LENGTH OF THE SUBSTEP.
      DO 150 I=2,NMBINS
        WP(I-1)=2.D0*PI*ALPHA*SHD*WBETA*DABS((1.D0/(ANGTCM*WVLNTH(I-1))
     1    - 1.D0/(ANGTCM*WVLNTH(I)))*
```

```
     2   (1.D0-1.D0/V/V/VARIND(MTRL,I-1)/VARIND(MTRL,I-1)))
 150  CONTINUE
C *** MAIN LOOP
C     SET INITIAL POSITION AND ZONE OF PRODUCTION
      DO 1560 K=1,NMBINS-1
         DO 160 I=1,3
            XCHR(I) = XCHR1(I)
            WT(I) = WT1(I)
            XB(I) = XB1(I)
160      CONTINUE
         NR = NR1
         NRC = NRC1
         IR = NR
         IRPRIM = NRC
C *** GET INDEX OF REFRACTION ***
200      XREF = VARIND(MTRL,K)
C *** IS INDEX OF REFRACTION ABOVE CUTOFF FOR CERENKOV? ***
         IF(XREF .LE. 1.D0) GO TO 1550
C  CALCULATE PHOTON ENERGY IN MEV
         EP = PLANKC/(ANGTCM*WVLNTH(K))
C *** CALCULATE COSINE FOR CERENKOV PHOTON IN MOVING FRAME
C ***     = 1 / (BETA * INDEX OF REFRACTION)
C ***     = RATIO OF SPEED OF LIGHT IN MEDIUM TO ELECTRON VELOCITY
         CPRO = 1.D0/(V*XREF)
C *** TALLY PHOTON NUMBER COUNT, WEIGHT, AND ENERGY PRODUCED HERE
         CHRNUM(NR,K) = CHRNUM(NR,K) + 1.D0
         CHRWAT(NR,K) = CHRWAT(NR,K) + WP(K)
         CHRENG(NR,K) = CHRENG(NR,K) + EP*WP(K)
C *** BRING POLAR ANGLE BACK INTO LAB FRAME ***
         CALL FOLD(CPOL,SPOL,CAZI,SAZI,CPRO,CZ,SZ,CX,SX)
C *** USE SAME INITIAL PHOTON WEIGHT
         WZERO = WP(K)
C *** SET DIRECTION COSINES AND PREPARE FOR RAY TRACE ***
         C(1) = SZ*CX
         C(2) = SZ*SX
         C(3) = CZ
C *** CONDUCT RAY TRACE OF CERENKOV PHOTON THROUGH GEOMETRY ***
         NUMCT = NUMCT + 1
C  SET INITIAL COLLISTION COUNTER
         KLIDE = 0
700   CALL PATH(NR,NRC,XCHR,C,ST,NRPC,NSC,XPI,XPO,CN)
C **** CHECK FORMATTING HERE ***
C *** IF NO ZONE IS FOUND THEN PHOTON ESCAPES
         IF(IRPRIM .LT. 0) THEN
            M = 5
            GO TO 1550
         ENDIF
         M = 3
C *** COMPUTE THE PHOTON WEIGHT ATTENUATION AND DETERMINE THE WEIGHT
C *** LEFT FOR FURTHER RAY TRACE.
         WNEW = WP(K)*DEXP(-ST*CHER(2,NR))
C *** UPDATE THE WEIGHT (CALCULATE THE WEIGHT ABSORBED IN ZONE)
         WABS = WP(K) - WNEW
         WP(K) = WNEW
C *** TALLY THE ABSORBED WEIGHT FOR THAT ZONE
```

```
         CHRABS(NR,K) = CHRABS(NR,K) + WABS
C THIS SECTION CREATES TALLIES FOR VIRTUAL SOURCE
         IF(IVIRS .EQ. 1) THEN
            ICVIR = IBFIND(C(3),NCVIR,CVIRB)
            IF(ICVIR .LE. 0) GO TO 1000
            SVIR = (HVIR - XCHR(3))/C(3)
            XVIR = XCHR(1) + SVIR*C(1)
            YVIR = XCHR(2) + SVIR*C(2)
            RVIR = DSQRT(XVIR*XVIR + YVIR*YVIR)
            IRVIR = IBFIND(RVIR,NRVIR,RVIRB)
            IF(IRVIR .LE. 0) GO TO 1000
            CTVIR = 1.D0
            STVIR = 0.D0
            IF(RVIR .GT. 0.D0) THEN
               CTVIR = XVIR/RVIR
               STVIR = YVIR/RVIR
            ENDIF
            AVIR = 0.D0
            CSQ = DSQRT(C(1)*C(1) + C(2)*C(2))
            IF(CSQ .LE. 0.D0) GO TO 900
            AVIR = (CTVIR*C(1) + STVIR*C(2))/CSQ
            IF(DABS(AVIR) .GT. 1.D0) AVIR = AVIR/DABS(AVIR)
            AVIR = DACOS(AVIR)
900         IAVIR = IBFIND(AVIR,NAVIR,AVIRB)
            IF(IAVIR .LE. 0) GO TO 1000
            VOLVIR = 2.D0*PI*(RVIRB(IRVIR + 1)**2-RVIRB(IRVIR)**2)
     1         *(CVIRB(ICVIR + 1) - CVIRB(ICVIR))
     2         *(AVIRB(IAVIR + 1) - AVIRB(IAVIR))
            SCOVOL(IAVIR,ICVIR,IRVIR)=
     1         SCOVOL(IAVIR,ICVIR,IRVIR)+WP(K)/VOLVIR
         ENDIF
C*************** END OF VIRTUAL SOURCE SECTION ********************
C *** INCREMENT THE NUMBER OF REFLECTIONS (COLLISIONS OF PHOTON)
1000     KLIDE = KLIDE + 1
C *** PUT AN UPPER LIMIT ON THE NUMBER OF REFLECTIONS ALLOWED
C ***    (IE. DON'T GET IN AN INFINITE LOOP BETWEEN WALLS)
         IF((KLIDE .GT. KALTOT).OR.(WP(K).LT.WZERO*1.D-3)) THEN
            WKILL = WKILL + WP(K)
            GO TO 1550
         ENDIF
C *** INITIALIZE SPECULAR AND DIFFUSE REFLECTION COEFFICIENTS
         SPECU = 0.D0
         DIFFU = 0.D0
C *** SET NEXT REGION INDEX
         NRP = NRPC
C *** CHECK TO SEE IF WE HAVE A NEXT REGION
C *** IF SO THEN GET THE TRUE SPECULAR AND DIFFUSE COEFFICIENTS
         IF(NRPC .GT. 0) NRP=IROR(NRPC)
         IF(NRP .GT. 0) THEN
            SPECU = CHER(3,NRP)
            DIFFU = CHER(4,NRP)
         ENDIF
C *** CHECK TO SEE IF PHOTON UNDERGOES SPECULAR OR DIFFUSE REFLECTION
         RA = RANF(IRAN)-SPECU
         IF(RA .LE. 0.D0) THEN
C *** SPECULAR REFLECTION ***
```

```
            CPRE = C(1)*CN(1) + C(2)*CN(2) + C(3)*CN(3)
1100        PSI = 2.D0*CPRE
C *** NEW DIRECTION = OLD DIRECTION - 2*(NORMAL COMPONENT)
C ***     VECTR2 = VECTR1 - 2*(NMLVECT DOT VECTR1)*NMLVECT
            C(1) = C(1) - PSI*CN(1)
            C(2) = C(2) - PSI*CN(2)
            C(3) = C(3) - PSI*CN(3)
C *** SET NEW POSITION
            DO 1200 J=1,3
               XCHR(J) = XPI(J)
1200        CONTINUE
C *** REPEAT UNTIL PHOTON TERMINATES ***
            GO TO 700
         ENDIF
C *** CHECK FOR DIFFUSE REFLECTION ***
         RA = RA - DIFFU
         IF(RA .LE. 0.D0) THEN
C *** SAMPLE RANDOM POLAR COSINE RELATIVE TO SURFACE NORMAL
            CP(3) = -RANF(IRAN)
C *** SINE OF POLAR SCATTERING ANGLE
            SINE = DSQRT(1.D0 - CP(3)*CP(3))
C ***AZIMUTHAL SCATTERING ANGLE RANDOM BETWEEN + OR - PI
            THE = PI*(2.D0*RANF(IRAN) - 1.D0)
            CP(1) = SINE*DCOS(THE)
            CP(2) = SINE*DSIN(THE)
C *** ROTATE DIRECTION COSINES BACK INTO LAB FRAME
            CALL ROTCPC(CN,CP,C)
C *** UPDATE CURRENT POSITON
            DO 1300 J=1,3
               XCHR(J) = XPI(J)
1300        CONTINUE
            GO TO 700
         ENDIF
C *** TRANSMIT THE CERENKOV PHOTON ***
C *** SET COSINE OF INCOMING RAY RELATIVE TO SURFACE NORMAL
         CPRE = C(1)*CN(1) + C(2)*CN(2) +C(3)*CN(3)
         YREF = 1.D0
C *** SET ZONE NUMBER
         NRP = NRPC
         IF(NRPC .GT. 0) NRP=IROR(NRPC)
         ACCEPT = 1.D0
C *** IF THERE IS A NEXT ZONE SET INDEX OF REFRACTION AND FRACTION
C *** ACCEPTED
         IF(NRP .GT. 0) THEN
            MTRL1 = IDINT(CHER(1,NRP))
            YREF = VARIND(MTRL1,K)
            ACCEPT = CHER(5,NRP)
         ENDIF
C *** TEST TO SEE IF THE PHOTON IS REFLECTED OR TRANSMITTED
         IF(RANF(IRAN) .GT. ACCEPT) GO TO 1100
C *** DOES SNELLS LAW ALLOW TRANSMITION? (SNELL'S LAW IN TERMS OF
C *** COSINE OF ANGLE SQUARED)
         CP2 = 1.D0 - XREF*XREF*(1.D0 - CPRE*CPRE)/(YREF*YREF)
C *** IF COSINE OF ANGLE SQUARED LESS THAN OR EQUAL ZERO THEN
C *** SPECULAR REFLECTION OCCURS (OUTSIDE CRITICAL ANGLE)
         IF(CP2 .LE. 0.D0) GO TO 1100
```

```
         SPRE = DSQRT(1.D0 - CPRE*CPRE)
         CAFT = DSQRT(CP2)
         SAFT = DSQRT(1.D0 - CP2)
         SRAT = SAFT/SPRE
         CRAT = CAFT - SRAT*CPRE
C *** DIRECTION COSINES AFTER ENTERING NEW ZONE IN LAB FRAME
         DO 1400 J=1,3
            C(J) = SRAT*C(J) + CRAT*CN(J)
1400     CONTINUE
C *** INCREMENT CERENKOV WEIGHT EXITING PREVIOUS ZONE
         CHROUT(NR,K) = CHROUT(NR,K) + WP(K)
C *** IS THERE A NEXT ZONE?
         IF(NRP .GE. 0) THEN
C ***INCREMENT CERENKOV WEIGHT ENTERING NEXT ZONE
            CHRENT(NRP,K) = CHRENT(NRP,K) + WP(K)
C *** UPDATE ZONE AND INDEX OF REFRACTION
            NR = NRP
            NRC = NRPC
            XREF = YREF
C *** UPDATE POSITION
            DO 1500 J=1,3
               XCHR(J) = XPO(J)
1500        CONTINUE
C *** REPEAT UNTIL ALL ZONES COMPLETED
            IF(NRP .LT. NRMAX) GO TO 700
         ENDIF
1550     CONTINUE
1560  CONTINUE
1600  RETURN
      END
C *** SUBROUTINE TO ROTATE COORDINATES BACK INTO LAB FRAME
      SUBROUTINE ROTCPC(CP,D,C)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION CP(3),D(3),C(3),E3(3),E2(3),E1(3)
      DO 100 J=1,3
         E3(J) = CP(J)
100   CONTINUE
      E22 = E3(1)*E3(1) + E3(2)*E3(2)
      IF(E22 .LE. 0.D0) THEN
         E2(1) = 1.D0
         E2(2) = 0.D0
      ELSE
         E22 = DSQRT(E22)
         E2(1) = -E3(2)/E22
         E2(2) = E3(1)/E22
      ENDIF
      E2(3) = 0.D0
      E1(1) = E2(2)*E3(3) - E2(3)*E3(2)
      E1(2) = E2(3)*E3(1) - E2(1)*E3(3)
      E1(3) = E2(1)*E3(2) - E2(2)*E3(1)
      DO 200 J=1,3
         C(J) = D(1)*E1(J) + D(2)*E2(J) + D(3)*E3(J)
200   CONTINUE
      RETURN
      END
```

```
      SUBROUTINE PATH(NR,NRG,X,C,ST,NRGP,NSCP,XPI,XPO,CN)
C *** RAY TRACING SUBROUTINE ****
*CA CNSTNT
*CA PARAMS
*CA PAREM
*CA STTS
*CA GOMLOC
*CA DBG
*CA ORGI
*CA SECZN
*CA COG
      COMMON/NRML/UN(3)
      DIMENSION X(3),C(3),XPO(3),XPI(3),CN(3)
C *** ACCEPT VERSION
      DIST = CZERO
      DIST0 = PINF
      IRPRIM = NRG
      IR = NR
      KLOOP = KLOOP + 1
      DO 100 I=1,3
         XB(I)=X(I)
         WT(I)=C(I)
100   CONTINUE
      ICALL = 0
      IZE = 0
      CALL DISTA(S)
      IF(IRPRIM .GE. 0) THEN
         ST = DIST
         DO 200 I=1,3
            XPI(I) = X(I) + (ST*0.99999D0)*C(I)
            XPO(I) = X(I) + (ST*1.00001D0)*C(I)
200      CONTINUE
         NRGP = IRPRIM
         NSCP = LSURF
         CALL NORML(NRG,LSAVE)
C *** SET NORMAL TO DIRECTION UNTIL NORMAL IS AVAILABLE
         DO 300 I=1,3
            CN(I) = -UN(I)
300      CONTINUE
      ENDIF
      RETURN
      END
       SUBROUTINE NORML(IRR,NASC)
C *** USER BEWARE:  MUCH OF THIS ROUTINE IS UNTESTED.  IT IS ASSUMED
C *** THAT XB+WT*DIST IS ON SURFACE LSURF OF BODY NASC.  THUS A NORMAL
C *** CALL MUST BE PROCEEDED BY A CALL TO G1 OR LOOKZ.
*CA CNSTNT
*CA PARAMS
*CA PAREM
*CA GOMLOC
*CA DBG
*CA ORGI
*CA SECZN
*CA COG
      COMMON /NRML/UN(3)
      DIMENSION XP(3),WP(3),X(3),H(3),IBOX1(3),IBOX2(3)
```

```
      DATA IBOX1/10,7,4/
      DATA IBOX2/4,10,7/
      LSUR = IABS(LSURF)
      DO 100 I=1,3
         XP(I) = XB(I) + DIST*WT(I)
100   CONTINUE
      N = LOCREG(IRR)
      NUM = NUMBOD(IRR)*4 + N - 4
      DO 200 I=N,NUM,4
         IF(NASC .EQ. I) GO TO 400
200   CONTINUE
      WRITE(6,300) IRR,NASC,(MA(I),I=N,NUM,4)
300   FORMAT(1X,'INVALID REGION OR BODY IN NORMAL.    IR =',I7,'NASC=',
     1   I7,/,(10I7))
      CALL PR(1)
      STOP
400   L = MA(I+1)
      ITYPE = MA(L+1)
      K = MA(L+4)
C             ARB  SPH  RCC  REC  TRC  ELL  BOX  WED  RPP
      GO TO (500,1200,1400,1500,1400,1600,1700,1500,1900), ITYPE
C *** ARB
500   I=K + 1 + 4*(LSUR - 1)
      DO 1110 J=1,3
         UN(J) = FPD(I+J)
1110  CONTINUE
      GO TO 2000
C *** SPH
1200  DO 1210 I=1,3
         UN(I) = (XP(I) - FPD(K+I+1))/FPD(K+5)
1210  CONTINUE
      GO TO 2000
C *** TRC AND RCC
1400  H2=0.D0
      DO 1410 I=1,3
         H(I)=FPD(K+4+I)
         H2=H2 + H(I)*H(I)
1410  CONTINUE
      GO TO (1415,1415,1435), LSUR
1415  H2 = DSQRT(H2)
      DO 1420 I=1,3
         UN(I) = H(I)/H2
1420  CONTINUE
      GO TO 2000
1435  DO 1440 I=1,3
         X(I) = XP(I) - FPD(K+1+I)
1440  CONTINUE
      XMU = 0.D0
      A2 = 0.D0
      DO 1445 I=1,3
         J = MOD(I,3) + 1
         A2 = A2 + (H(I)*X(J) - H(J)*X(I))**2
         XMU = XMU + FPD(K+4+I)*X(I)
1445  CONTINUE
      R = FPD(K+8) - FPD(K+9)
      IF(ITYPE .EQ. 3) R = 0.D0
```

```
      B1 = R/DSQRT(H2*(H2 + R*R))
      B2 = 1.D0/DSQRT(A2*(H2 + R*R))
      DO 1450 I=1,3
         UN(I) = B2*(X(I)*H2 - H(I)*XMU) + B1*H(I)
1450  CONTINUE
      GO TO 2000
1500  WRITE(6,1501) ITYPE
1501  FORMAT(1X,'NOT IMPLEMENTED IN NORMAL.   ITYPE =',I5)
      STOP
C *** ELL
1600  DX = 0.D0
      AN = 0.D0
      C2 = FPD(K+8)**2/4.D0
      DO 1620 I=1,3
         IA = I + K + 1
         X(I) = XP(I) - .5D0*(FPD(IA) + FPD(IA+3))
         H(I) = .5D0*(FPD(IA+3) - FPD(IA))
         DX = DX + X(I)*H(I)
1620  CONTINUE
      DO 1630 I=1,3
         UN(I) = C2*X(I) - DX*H(I)
         AN = AN + UN(I)*UN(I)
1630  CONTINUE
      IF(AN .GE. 1.D-12) THEN
         AN = DSQRT(AN)
         DO 1635 I=1,3
            UN(I) = UN(I)/AN
1635     CONTINUE
         GO TO 2000
      ENDIF
1650  WRITE(6,1651) NBO,LSURF,(XP(I),I=1,3)
1651  FORMAT(1X,'ROUND-OFF ERROR IN NORMAL.  NBO=',I5,'LSURF=',I5,
     1   'XP=',3E12.5)
      STOP
C *** BOX
1700  L = 1 + (LSUR - 1)/2
      I1 = IBOX1(L)
      I2 = IBOX2(L)
      DO 1720 I=1,3
         X(I) = FPD(K+I1+I)
         H(I) = FPD(K+I2+I)
1720  CONTINUE
      AN = 0.D0
      DO 1730 I=1,3
         J = MOD(I,3) + 1
         JJ = MOD(I+1,3) + 1
         UN(I) = X(J)*H(JJ) - X(JJ)*H(J)
         AN = AN + UN(I)*UN(I)
1730  CONTINUE
      IF(AN .LT. 1.0D-12) GO TO 1650
      AN = DSQRT(AN)
      DO 1735 I=1,3
         UN(I) = UN(I)/AN
1735  CONTINUE
```

```
      GO TO 2000
C *** RPP
1900  DO 1905 I=1,3
         UN(I) = 0.D0
1905  CONTINUE
      GO TO (1910,1910,1920,1920,1930,1930), LSUR
1910  UN(2) = 1.D0
      GO TO 2000
1920  UN(1) = 1.D0
      GO TO 2000
1930  UN(3) = 1.D0
2000  XMU = 0.D0
      DO 2005 I=1,3
         XMU = XMU + WT(I)*UN(I)
2005  CONTINUE
      XMU = -1.D0*XMU
C     AN = SIGN(1.D0, XMU)
      IF(XMU .LT. 0.D0) THEN
         AN = -1.D0
      ELSE
         AN = 1.D0
      ENDIF
      XMU = -1.D0*XMU
      DO 2010 I=1,3
         UN(I) = AN*UN(I)
2010  CONTINUE
      RETURN
      END
      FUNCTION IBFIND(X,MX,XB)
C *** IBFIND FINDS CORRECT TALLY BINS ***
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION XB(100)
      IBFIND=0
      IF(X .LT. XB(1)) GO TO 7777
      DO 1000 I=1,MX
         IF(X .LE. XB(I+1))  GO TO 1010
1000  CONTINUE
      GO TO 7777
1010  IBFIND=I
7777  RETURN
      END
```

APPENDIX C. SAMPLING SUBROUTINE LISTING

```
*IDENT DEFINE
*DEFINE IBM
*DEFINE DOUBLE
*DEFINE ACCEPT
*IDENT,PHILLIPS
*IDENT,PERMT
*D,PARAMS.17
      PARAMETER (KPTMAX=10000,        INSTAT=100,
*I,HIST.94
      COM = CZERO
*I,HIST.223
        IF((IB .EQ. 1) .AND. (IHIST .LE. 50)) THEN
           IF(IHIST .EQ. 1) WRITE(6,801)
C  SEND ADITIONAL OUTPUT TO OUTPUT UNIT 6
801     FORMAT(1X,1HI,2X,2HLB,7X,1HX,14X,1HY,14X,1HZ,
     1      13X,1HU,13X,1HV,12X,1HW,12X,3HCOM,10X,7HENERGY /)
           WRITE(6,802) IHIST,LB,XB,WT,COM,T
 802       FORMAT(2I3,8(2X,1PE12.5))
C
         ENDIF
C
*IDENT,CKVTR
*I,CALC.78
     6   ,AIRP,CO2P,TMPKEL
*I,OUT.30
C  CERENKOV ADDITIONS TO COMMON BLOCK
      COMMON /OUT/
     1   CHER(5,100),CHRNUM(100,100),
     2   CHRWAT(100,100),CHRENG(100,100),CHRABS(100,100),
     3   CHROUT(100,100),CHRENT(100,100),TRNUM(100,100),
     4   TRWAT(100,100),TRENG(100,100),TRABS(100,100),
     5   TROUT(100,100),TRENT(100,100),NRVIR,NCVIR,NAVIR,
     6   CVIRB(11),AVIRB(11),RVIRB(11),VARIND(100,100),WVLNTH(100),
     7   SCOVOL(10,10,10),HVIR,ITRAD,NRBOTH,ICKV,IVIRS,KALTOT,
     8   LBTRAD,NBOTRD,JSRTRD,NCALL,NMBINS,WKILL
*I,INPUT.54
      DIMENSION WVLNT(100),VARIN(100,100)
C*************************************************************************
C******THIS SECTION ASSIGNS VALUES TO THE TABLE OF INDEX OF     ******
C******REFRACTION AND WAVELENGTH.  THE TABLES CREATED ARE       ******
C******STRUCTURED TO COVER WAVELENGTHS IN 200 ANGSTROM BINS     ******
C******FROM 1800 THROUGH 5000 ANGSTROMS, AND IN 500 ANGSTROM   ******
C******BINS FROM 5500 THROUGH 10000 ANGSTROMS.                 ******
C******THE VARIND TABLE CONTAINS INDICES OF REFRACTION FOR     ******
C******EACH MATERIAL.                                          ******
C******                                                        ******
C******VARIND(I,J)          --  INDEX OF REFRACTION FOR MATERIAL******
C******                          MATERIAL I ASSOCIATED WITH    ******
C******                          WAVELENGTH BIN J              ******
C******                                                        ******
C******WVLNTH(J)            --  WAVELENGTH VALUE FOR BIN J    ******
```

```
C*****                                                                *****
C**********************************************************************
C
C  WAVELENGTHS
      DATA (WVLNT(I),I=1,27)/ 1800,2000,
     1   2200,2400,2600,2800,3000,
     2   3200,3400,3600,3800,4000,
     3   4200,4400,4600,4800,5000,
     4   5500,6000,6500,7000,7500,
     5   8000,8500,9000,9500,10000 /
C  VACUUM
      DATA (VARIN(1,I),I=1,27)/27*1.D0/
C  AIR
      DATA (VARIN(2,I),I=1,27)/
     1  1.00034D0,1.00031D0,1.00030D0,1.00030D0,1.00029D0,
     2  1.00029D0,1.00029D0,1.00029D0,1.00028D0,1.00028D0,
     3  1.00028D0,1.00028D0,1.00028D0,1.00028D0,1.00028D0,
     4  1.00028D0,1.00028D0,1.00028D0,1.00028D0,1.00028D0,
     5  1.00028D0,1.00027D0,1.00027D0,1.00027D0,1.00027D0,
     6  1.00027D0,1.00027D0 /
C  CARBON DIOXIDE (STANDARD ATMOSPHERE)
      DATA (VARIN(3,I),I=1,27)/
     1  1.00055D0,1.00052D0,1.00051D0,1.00050D0,1.00049D0,
     2  1.00048D0,1.00048D0,1.00047D0,1.00047D0,1.00046D0,
     3  1.00046D0,1.00046D0,1.00046D0,1.00046D0,1.00045D0,
     4  1.00045D0,1.00045D0,1.00045D0,1.00045D0,1.00045D0,
     5  1.00045D0,1.00045D0,1.00045D0,1.00044D0,1.00044D0,
     6  1.00044D0,1.00044D0 /
C  GLASS TYPE 458/678(MIL-G-174) (FUSED SILICA DENSITY 2.202 G/CM**3)
      DATA (VARIN(4,I),I=1,27)/
     1  1.58529D0,1.55051D0,1.52845D0,1.51333D0,1.50352D0,
     2  1.49565D0,1.48779D0,1.48274D0,1.47884D0,1.47554D0,
     3  1.47283D0,1.47012D0,1.46830D0,1.46648D0,1.46492D0,
     4  1.48363D0,1.46233D0,1.45991D0,1.45804D0,1.45664D0,
     5  1.45529D0,1.45424D0,1.45332D0,1.45250D0,1.45175D0,
     6  1.45107D0,1.45042D0 /
C  CRYSTAL QUARTZ
      DATA (VARIN(5,I),I=1,27)/
     1  1.66006D0,1.65087D0,1.62626D0,1.61011D0,1.60158D0,
     2  1.59306D0,1.58453D0,1.57600D0,1.56747D0,1.56413D0,
     3  1.56080D0,1.55779D0,1.55554D0,1.55349D0,1.55194D0,
     4  1.55039D0,1.54884D0,1.54616D0,1.54393D0,1.54247D0,
     5  1.54101D0,1.53955D0,1.53839D0,1.53744D0,1.53663D0,
     6  1.53581D0,1.53502D0 /
C
*I,INPUT.436
C  CERENKOV ADDITIONS TO DEFAULT INPUT PARAMETERS
        NMBINS=27
        NCALL=0
        ICKV=0
        IVIRS=0
        ITRAD=0
C  END OF CERENKOV ADDITIONS
*I,INPUT.575
C**************************
```

```
C  CERENKOV
C**************************
          ELSE IF (KOP('CERENKOV') .GE. 0) THEN
             IMATCH = 1
             ICKV = 1
C  SET PRESSURE FOR AIR IN STANDARD ATMOSPHERES
             AIRP = PARM(1)
C  SET PRESSURE FOR CO2 IN STANDARD ATMOSPHERES
             CO2P = PARM(2)
C  SET TEMPERATURE IN KELVIN, THEN SCALE TO 293 KELVIN
             TMPKEL = PARM(3)
             TMPKEL = TMPKEL/293.D0
             DO 93774 I1=1,NMBINS
                VARIND(1,I1)=VARIN(1,I1)
C  INDICES OF REFRACTION - 1 CHANGE PROPORTIONAL TO PRESSURE CHANGE
                VARIND(2,I1)=(VARIN(2,I1)-1.D0)*AIRP/TMPKEL + 1.D0
                VARIND(3,I1)=(VARIN(3,I1)-1.D0)*CO2P/TMPKEL + 1.D0
93774        CONTINUE
             DO 93884 J1=4,20
                DO 93874 I1=1,NMBINS
                   VARIND(J1,I1)=VARIN(J1,I1)
93874           CONTINUE
93884        CONTINUE
             DO 93894 I1=1,NMBINS
                WVLNTH(I1)=WVLNT(I1)
93894        CONTINUE
             KALTOT = PARM(4)
             DO 3034 JJJ=1,NZON
                CALL OPREAD(1,INUNIT,IECHO,IVAL,EOFLAG)
C
C  CHECK INPUT FILE FOR COMPLETE OPTICAL DATA
C
                IF(EOFLAG) THEN
                   WRITE(*,*) 'PREMATURE END OF OPTICAL DATA'
                   STOP
                ENDIF
                IF (KOP('+') .GE. 0) THEN
C
C  ASSIGN VALUES TO CERENKOV INPUT MATERIAL NUMBER FOR ZONE JJJ
                   CHER(1,JJJ) = PARM(1)
C  EXTINCTION COEFFICIENT (1/CM) -- ATTENUATION COEFFICIENT
                   CHER(2,JJJ) = PARM(2)
C  FRACTION OF LIGHT TO BE MIRROR REFLECTED FROM ZONE WALLS
                   CHER(3,JJJ) = PARM(3)
C  FRACTION OF LIGHT TO BE DIFFUSE REFLECTED FROM ZONE WALLS
                   CHER(4,JJJ) = PARM(4)
C  FRACTION OF LIGHT TO BE ACCEPTED FOR ENTRANCE INTO ZONE
                   CHER(5,JJJ) = PARM(5)
C
                ELSE
                   WRITE(*,8903)
8903               FORMAT(1X,'ILLEGAL CKV OR VIRS ZONE DATA')
                   GO TO 9999
                ENDIF
3034            CONTINUE
C**************************
```

```
C  VIRTUAL-SOURCE
C*************************
                ELSE IF (KOP('VIRTUAL-SOURCE') .GE. 0) THEN
                   IMATCH = 1
                   IVIRS = 1
                   HVIR = PARM(1)
                   NRVIR = PARM(2)
                   NCVIR = PARM(3)
                   NAVIR = PARM(4)
                   READ(INUNIT,*,END=9051,ERR=9052)
     1                (RVIRB(IR),IR=1,NRVIR) ,RVIRB(NRVIR + 1)
                   READ(INUNIT,*,END=9051,ERR=9052)
     1                (CVIRB(IC),IC=1,NCVIR),CVIRB(NCVIR + 1)
                   READ(INUNIT,*,END=9051,ERR=9052)(AVIRB(IA),
     1                IA=1,NAVIR) ,AVIRB(NAVIR + 1)
C*************************************
C  TRANSITION RADIATION
C*************************************
                ELSE IF(KOP('TRANSITION-RADIATION') .GE. 0) THEN
                   IMATCH = 1
                   ITRAD = 1
                   LBTRAD = PARM(1)
                   NBOTRD = PARM(2)
                   JSRTRD = PARM(3)
*I,INPUT.1178
      IF(ICKV .EQ. 1) THEN
C  CERENKOV OPTICAL AND VIRTUAL SOURCE DATA.......
      WRITE(6,9005)
9005  FORMAT(6H  ZONE,6X,6H MTRL ,6X,6HABSORB,6X,6HMIRROR,5X,7HDIFFUSE
     1   ,6X,6HACCEPT,4X,8HTRANSMIT)
      DO 90051 I=1,LZMAX
C  FRACTION OF LIGHT TO BE TRANSMITTED OUT THROUGH ZONE BOUNDARY
         FST = 1 - CHER(3,I) - CHER(4,I)
         WRITE(6,90050)I,(CHER(J,I),J=1,5),FST
90050    FORMAT(I6,1P6E12.4)
90051 CONTINUE
C
      ENDIF
C
      IF(ITRAD .EQ. 1) THEN
         WRITE(6,90311) LBTRAD,NBOTRD,JSRTRD
90311    FORMAT(/' TRANSITION RADIATION LOCATION, ZONE BODY SURFACE'
     1      ,3I6)
C
      ENDIF
C
      IF (IVIRS .EQ. 1) THEN
         WRITE(6,90300) HVIR,NRVIR,NCVIR,NAVIR
90300    FORMAT(/17H VIRTUAL SOURCE Z, E12.4
     1      /' VIRTUAL SOURCE TALLY BINS, RADIAL, POLAR, AZIMUTH,'
     2     , 3I6)
         WRITE(6,9050)(RVIRB(IR),IR=1,NRVIR),RVIRB(NRVIR + 1)
         WRITE(6,9055)(CVIRB(IC),IC=1,NCVIR),CVIRB(NCVIR + 1)
         WRITE(6,9060)(AVIRB(IA),IA=1,NAVIR),AVIRB(NAVIR + 1)
9050     FORMAT(8H RADIAL  ,10E12.4)
9055     FORMAT(8H POLAR   ,10E12.4)
```

```
9060     FORMAT(8H AZIMUTH ,10E12.4)
C
      ENDIF
C
*I,PREP.659
      IF(ICKV .EQ. 1) THEN
         WKILL = CZERO
         DO 241 LLL=1,100
            DO 2401 JJJ=1,100
               CHRNUM(LLL,JJJ) = CZERO
               CHRWAT(LLL,JJJ) = CZERO
               CHRENG(LLL,JJJ) = CZERO
               CHRABS(LLL,JJJ) = CZERO
               CHROUT(LLL,JJJ) = CZERO
               CHRENT(LLL,JJJ) = CZERO
2401        CONTINUE
241      CONTINUE
C
      ENDIF
C
      IF(IVIRS .EQ. 1) THEN
         DO 244 IR=1,NRVIR
            DO 243 IC=1,NCVIR
               DO 242 IA=1,NAVIR
                  SCOVOL(IA,IC,IR) = CZERO
242            CONTINUE
243         CONTINUE
244      CONTINUE
C
      ENDIF
C
*I,OUTPUT.47
      DIMENSION
     1     CHRN(100),CHRW(100),CHRE(100),CHRA(100),CHRO(100),CHRI(100)
      INTEGER ISIGA(100),ISIGB(100),ISIGC(100),ISIGD(100),ISIGE(100),
     1        ISIGF(100),IWVL(100),ISIG1(100),ISIG2(100),ISIG3(100),
     2        ISIG4(100),ISIG5(100),ISIG6(100)
*I,OUTPUT.561
      IF(ICKV .EQ. 1) THEN
         WTESC = CZERO
         WTABS = CZERO
         WTOT = CZERO
C  SCALE RESULTS TO RESULTS PER HISTORY
         WKILL = WKILL/CIMAX
         DO 66 I=1,LZMAX
            DO 56110 J=1,NMBINS-1
               CHRNUM(I,J)=(CHRNUM(I,J)/(CIMAX))
               CHRWAT(I,J)=CHRWAT(I,J)/CIMAX
               CHRENG(I,J)=CHRENG(I,J)/CIMAX
               CHRABS(I,J)=CHRABS(I,J)/CIMAX
               CHROUT(I,J)=CHROUT(I,J)/CIMAX
               CHRENT(I,J)=CHRENT(I,J)/CIMAX
56110       CONTINUE
66       CONTINUE
         DO 10225 I=1,100
            CHRN(I)=CZERO
```

```
            CHRW(I)=CZERO
            CHRE(I)=CZERO
            CHRA(I)=CZERO
            CHRO(I)=CZERO
            CHRI(I)=CZERO
10225     CONTINUE
C  COMPUTE THE TOTALS FOR EACH ZONE
          DO 11230 I=1,LZMAX
             DO 11225 J=1,NMBINS-1
                CHRN(I)=CHRN(I)+CHRNUM(I,J)
                CHRW(I)=CHRW(I)+CHRWAT(I,J)
                CHRE(I)=CHRE(I)+CHRENG(I,J)
                CHRA(I)=CHRA(I)+CHRABS(I,J)
                CHRO(I)=CHRO(I)+CHROUT(I,J)
                CHRI(I)=CHRI(I)+CHRENT(I,J)
11225        CONTINUE
11230     CONTINUE
          DO 14344 I=1,LZMAX
             WTOT = WTOT + CHRW(I)
             WTABS = WTABS + CHRA(I)
14344     CONTINUE
          WTESC = CHRI(LZMAX)
          WTCON = (WTABS + WTESC + WKILL)/WTOT
          TEMP(1) = WTCON
          CALL STATS(TEMP,ISIG,1,KPUT)
          WTCON = TEMP(1)
C  CALCULATE THE AVERAGE VALUES OF THE TOTALS AND THEIR ERRORS
          CALL STATS(CHRN,ISIG1,LZMAX,KPUT)
          CALL STATS(CHRW,ISIG2,LZMAX,KPUT)
          CALL STATS(CHRE,ISIG3,LZMAX,KPUT)
          CALL STATS(CHRA,ISIG4,LZMAX,KPUT)
          CALL STATS(CHRO,ISIG5,LZMAX,KPUT)
          CALL STATS(CHRI,ISIG6,LZMAX,KPUT)
       ENDIF
C
       IF (IVIRS .EQ. 1) THEN
          DO 96 IR=1,NRVIR
             DO 86 IC=1,NCVIR
                DO 76 IA=1,NAVIR
                   SCOVOL(IA,IC,IR)=SCOVOL(IA,IC,IR)/CIMAX
76              CONTINUE
86           CONTINUE
96        CONTINUE
C
       ENDIF
C
*I,OUTPUT.1375
       IF(ICKV .EQ. 1) THEN
C**********************CHANGES ADDED HERE**********************
          NPUT=NMBINS-1
          DO 11220 I=1,LZMAX
             WRITE(NPRT,9000) I
9000         FORMAT(/,'ZONE =',I3,/,
     1        'WVLNTH',T14,'NUMBER',T22,'STAT',T33,'WEIGHT',T41,'STAT',
     2        T52,'ENERGY',T60,'STAT',T71,'ABSORB',T79,'STAT',T90,
     3        ' LEAVE',T97,'STAT',T108,' ENTER',T115,'STAT',/,
```

```
     1       '------',T14,'------',T22,'----',T33,'------',T41,'----',
     2        T52,'------',T60,'----',T71,'------',T79,'----',T90,
     3        '------',T97,'----',T108,'------',T115,'----',/)
             DO 11110 J=1,NMBINS-1
               TEMP(J)=CHRNUM(I,J)
11110        CONTINUE
             CALL STATS(TEMP,ISIGA,NPUT,KPUT)
             DO 11115 J=1,NMBINS-1
               CHRNUM(I,J)=TEMP(J)
11115        CONTINUE
             DO 11120 J=1,NMBINS-1
               TEMP(J)=CHRWAT(I,J)
11120        CONTINUE
             CALL STATS(TEMP,ISIGB,NPUT,KPUT)
             DO 11125 J=1,NMBINS-1
               CHRWAT(I,J)=TEMP(J)
11125        CONTINUE
             DO 11130 J=1,NMBINS-1
               TEMP(J)=CHRENG(I,J)
11130        CONTINUE
             CALL STATS(TEMP,ISIGC,NPUT,KPUT)
             DO 11135 J=1,NMBINS-1
               CHRENG(I,J)=TEMP(J)
11135        CONTINUE
             DO 11140 J=1,NMBINS-1
               TEMP(J)=CHRABS(I,J)
11140        CONTINUE
             CALL STATS(TEMP,ISIGD,NPUT,KPUT)
             DO 11145 J=1,NMBINS-1
               CHRABS(I,J)=TEMP(J)
11145        CONTINUE
             DO 11150 J=1,NMBINS-1
               TEMP(J)=CHROUT(I,J)
11150        CONTINUE
             CALL STATS(TEMP,ISIGE,NPUT,KPUT)
             DO 11155 J=1,NMBINS-1
               CHROUT(I,J)=TEMP(J)
11155        CONTINUE
             DO 11160 J=1,NMBINS-1
               TEMP(J)=CHRENT(I,J)
11160        CONTINUE
             CALL STATS(TEMP,ISIGF,NPUT,KPUT)
             DO 11165 J=1,NMBINS-1
               CHRENT(I,J)=TEMP(J)
11165        CONTINUE
             DO 11170 J=1,17
               IWVL(J)=1600 + J*200
11170        CONTINUE
             DO 11180 J=18,27
               IWVL(J)=5000 + (J-17)*500
11180        CONTINUE
             DO 11190 J=1,NMBINS-1
               WRITE(NPRT,11181) IWVL(J),CHRNUM(I,J),ISIGA(J),
     1           CHRWAT(I,J),
     2           ISIGB(J),CHRENG(I,J),ISIGC(J),CHRABS(I,J),ISIGD(J),
```

```
     3          CHROUT(I,J),ISIGE(J),CHRENT(I,J),ISIGF(J)
11181         FORMAT(I5,T8,1PE12.4,T22,I3,T27,1PE12.4,T41,I3,T46,
     1          1PE12.4,
     2          T60,I3,T65,1PE12.4,T79,I3,T84,1PE12.4,T97,I3,T102,
     3          1PE12.4,T115,I3)
11190       CONTINUE
11220     CONTINUE
          WRITE(NPRT,93867)
93867     FORMAT(/,'TOTALS FOR ALL ZONES',/,
     1        'ZONE',T14,'NUMBER',T22,'STAT',T33,'WEIGHT',T41,'STAT',
     2         T52,'ENERGY',T60,'STAT',T71,'ABSORB',T79,'STAT',T90,
     3         ' LEAVE',T97,'STAT',T108,' ENTER',T115,'STAT',/,
     1       '------',T14,'------',T22,'----',T33,'------',T41,'----',
     2        T52,'------',T60,'----',T71,'------',T79,'----',T90,
     3        '------',T97,'----',T108,'------',T115,'----',/)
          DO 12190 J=1,LZMAX
             WRITE(NPRT,12181) J,CHRN(J),ISIG1(J),
     1          CHRW(J),
     2          ISIG2(J),CHRE(J),ISIG3(J),CHRA(J),ISIG4(J),
     3          CHRO(J),ISIG5(J),CHRI(J),ISIG6(J)
12181        FORMAT(I5,T8,1PE12.4,T22,I3,T27,1PE12.4,T41,I3,T46,
     1          1PE12.4,
     2          T60,I3,T65,1PE12.4,T79,I3,T84,1PE12.4,T97,I3,T102,
     3          1PE12.4,T115,I3)
12190     CONTINUE
          WRITE(NPRT,12191) WTCON
12191     FORMAT(/,1X,'THE WEIGHT CONSERVATION FRACTION IS ',E12.4)
       ENDIF
C**************************END OF CHANGED OUTPUT**************************
90100 FORMAT(I3,3X,6(E12.4,I3))
       IF(IVIRS .EQ. 1) THEN
          WRITE(NPRT,90200)
90200     FORMAT(/'CERENKOV VIRTUAL SOURCE, PHOTONS/SQCM/STR')
          DO 6030 IVR=1,NRVIR
             WRITE(NPRT,90300) RVIRB(IVR),RVIRB(IVR+1)
90300        FORMAT(' R-MIN',E12.4/' R-MAX',E12.4,24X,
     1          ' UPPER AND LOWER POLAR COSINES ')
             DO 6020 LVC=1,NCVIR,5
                MVC=MIN0(LVC+4,NCVIR)
                WRITE(NPRT,9040)(CVIRB(IVC),IVC=LVC,MVC)
                WRITE(NPRT,9050)(CVIRB(IVC+1),IVC=LVC,MVC)
9040            FORMAT(23X,'MINIMUM',5X,'MAXIMUM',6E15.4)
9050            FORMAT(23X,'AZIMUTH',5X,'AZIMUTH',6E15.4)
                DO 6010 IVA=1,NAVIR
                   L=0
                   DO 6000 IVC=LVC,MVC
                      L=L+1
                      TEMP(L)=SCOVOL(IVA,IVC,IVR)
6000               CONTINUE
                   CALL STATS(TEMP,ISIG,L,KPUT)
                   WRITE(NPRT,9060)AVIRB(IVA),AVIRB(IVA+1),
     1                (TEMP(IVC),ISIG(IVC),IVC=1,L)
9060               FORMAT(18X,2E12.4,6(E12.2,I3))
6010            CONTINUE
6020        CONTINUE
```

```
6030     CONTINUE
C
      ENDIF
C
*I,OUTPUT.1383
      IF(ICKV .EQ. 1) THEN
         WKILL = CZERO
         DO 112 J=1,LZMAX
            DO 111 IJ=1,100
               CHRNUM(J,IJ)=CZERO
               CHRWAT(J,IJ)=CZERO
               CHRENG(J,IJ)=CZERO
               CHRABS(J,IJ)=CZERO
               CHROUT(J,IJ)=CZERO
               CHRENT(J,IJ)=CZERO
 111        CONTINUE
112      CONTINUE
      ENDIF
C
      IF(IVIRS .EQ. 1) THEN
         DO 115 IR=1,NRVIR
            DO 114 IC=1,NCVIR
               DO 113 IA=1,NAVIR
                  SCOVOL(IA,IC,IR)=CZERO
113            CONTINUE
114         CONTINUE
115      CONTINUE
C
      ENDIF
C
*I,INPUT.1853
9051  WRITE(*,9070)
9070  FORMAT
     1   ('0PREMATURE EOF WHILE READING CKV OR VIRS DATA')
      GO TO 9999
9052  WRITE(*,9071)
9071  FORMAT
     1   ('0ILLEGAL DATA IN FIELD WHILE READING CKV OR VIRS DATA')
      GO TO 9999
C
*I,EHIST.522
      IF (ICKV .EQ. 1) THEN
C *** SAVE ZONE INDEX FOR POSSIBLE CALL TO TRANSRAD
         IRSAV = IR
         IRPSAV = IRPRIM
         DISADD=DIST0
         IF(MARK .NE. 1) DISADD=DIST + 1.D-07
         XCHR=X + DISADD*STH(1)*CPH(1)
         YCHR=Y + DISADD*STH(1)*SPH(1)
         ZCHR=Z + DISADD*CTH(1)
         CALL CKVRAD
     1      (XCHR,YCHR,ZCHR,CTH,STH,CPH,SPH,W,T)
C *** REINSTATE ZONE INDEX FOR POSSIBLE CALL TO TRANSRAD
         IR = IRSAV
         IRPRIM = IRPSAV
```

```
          IF(IRPRIM .LT. 0) RETURN
C
       END IF
*I,DISTA.133
       NBOSAV = MA(LSAVE)
*D,PAREM.6
     $  KLOOP,    LOOP,      ITYPE,    NBOSAV
*I,KNOCK.367
C ***************************************************************************
C *CERENKOV PRODUCTION SELECTED RANDOMLY ALONG A SUBSTEP*
C ***************************************************************************
       SUBROUTINE CKVRAD
      1   (XS,YS,ZS,CPOL,SPOL,CAZI,SAZI,WBETA,EBETA)
C
C  VARIABLE DESCRIPTIONS
C
C  ACCEPT               FRACTION OF CERENKOV RADIATION ACCEPTED INTO
C                          ZONE
C  ALPHA                1./137.0 (FINE STRUCTURE CONSTANT)
C  ANGTCM               1.E-8 (AN ANGSTROM IN CENTIMETERS)
C  C(1)                 X PRESENT DIRECTION COSINE
C  C(2)                 Y PRESENT DIRECTION COSINE
C  C(3)                 Z PRESENT DIRECTION COSINE
C  CAFT                 COSINE AFTER REFLECTION
C  CAZI                 COSINE OF AZIMUTHAL SCATTERING ANGLE
C*************CERENKOV INPUTS*********
C  CHER(1,J)            MATERIAL NUMBER FOR ZONE J
C                          1 = VACUUM
C                          2 = AIR
C                          3 = CO2
C                          4 = GLASS
C                          5 = QUARTZ
C  CHER(2,J)            EXTINCTION COEFFICIENT (1/CM)
C  CHER(3,J)            FRACTION OF LIGHT TO BE MIRROR REFLECTED
C                          FROM ZONE WALLS
C  CHER(4,J)            FRACTION OF LIGHT TO BE DIFFUSE REFLECTED
C                          FROM ZONE WALLS
C  CHER(5,J)            FRACTION OF LIGHT TO BE ACCEPTED FOR
C                          ENTRANCE INTO ZONE
C*******CERENKOV OUTPUTS********
C
C  CHRNUM(J,K)          NUMBER OF CERENKOV PHOTONS PRODUCED IN ZONE J
C                          FROM WAVELENGTH BIN K
C                          PER INCIDENT SOURCE PARTICLE
C  CHRWAT(J,K)          CERENKOV WEIGHT PRODUCED IN ZONE J
C                          FROM WAVELENGTH BIN K PER INCIDENT
C                          SOURCE PARTICE WEIGHT OF 1.0
C  CHRENG(J,K)          CERENKOV ENERGY PRODUCED IN ZONE J
C                          FROM WAVELENGTH BIN K PER INCIDENT
C                          SOURCE PARTICLE
C                          = CHRENG(I) + EP*WP
C  CHRABS(J,K)          CERENKOV WEIGHT ABSORBED (KILLED) IN ZONE J
C                          FROM WAVELENGTH BIN K PER
C                          INCIDENT SOURCE PARTICLE
C                          = CHRABS(J) + WNEW  OR WABS
C  CHROUT(J,K)          CERENKOV WEIGHT THAT EXITS ZONE J
```

```
C                          FROM WAVELENGTH BIN K PER
C                          INCIDENT SOURCE PARTICLE
C                          = CHROUT(J) + WP
C  CHRENT(J,K)          CERENKOV WEIGHT THAT ENTERS ZONE (J+1)
C                          FROM WAVELENGTH BIN K PER
C                          INCIDENT SOURCE PARTICLE
C                          = CHRENT(J+1) + WP
C*****************************
C  CN(J)                NORMAL FROM THIS REGION TOWARDS NEXT REGION
C  CP(J)                DIRECTION COSINES IN MOVING FRAME
C  CP2                  COSINE SQUARED
C  POL                  COSINE OF POLAR SCATTERING ANGLE
C  CPRE                 SUM OF SQUARES OF CURRENT DIRECTION COSINES
C  CPRO                 PRODUCTION COSINE IN THE MOVING FRAME
C  CSQ                  SQUARE ROOT OF SUM OF SQUARES OF X AND Y DIRECTION
C                          COSINES
C  CX                   X DIRECTION COSINE
C  CZ                   Z DIRECTION COSINE
C  DIFFU                PROBABILITY FOR DIFFUSE REFLECTION
C  EBETA                ELECTRON ENERGY
C  EE                   GAMMA SQUARED
C  EP                   ENERGY OF CERENKOV PHOTON
C  FST                  FRACTION OF LIGHT TO BE TRANSMITTED OUT
C                          THROUGH ZONE BOUNDARY
C                          = 1.0 - CHER(3,J) - CHER(4,J)
C  J                    COUNTER
C  KALTOT               MAXIMUM NUMBER OF ALLOWED REFLECTIONS
C  KLIDE                COUNTER FOR NUMBER OF REFLECTIONS
C  NR                   PRESENT USER REGION
C  NRC                  PRESENT CODE REGION
C  NRPC                 NEXT CODE REGION
C  NRMAX                MAX ZONE NUMBER
C  NSC                  SURFACE CROSSED BY RAY
C  NZON                 ZONE NUMBER
C  PI                   3.14159
C  PLANKC               1.2405E-10
C  RA                   RANDOM NUMBER
C  RANF(ARG)            RANDOM NUMBER PRODUCING FUNCTION
C                          ARG = 0    PRODUCES UNIFORM RANDOM NUMBER
C  RVIR                 VIRTUAL SOURCE RADIUS
C  SAFT
C  SAZI                 SINE OF AZIMUTHAL SCATTERING ANGLE
C  SCOVOL(J,J,J)        DATA FOR VIRTUAL SOURCE
C  SHD                  LENGTH OF ELECTRON SUBSTEP IN CM
C  SIG                  PRODUCTION OF CERENKOV PHOTONS PER CM PER MEV
C  SPECU                PROBABILITY FOR SPECULAR REFLECTION
C  SPOL                 SINE OF POLAR SCATTERING ANGLE
C  ST                   DISTANCE TO BOUNDARY
C  STP                  SAMPLED LENGTH ALONG ELECTRON SUBSTEP (CM)
C  TIME
C  V                    RATIO OF ELECTON VELOCITY TO SPEED OF LIGHT (BETA)
C  V2                   BETA SQUARED
C  V2N2                 BETA SQUARED TIMES INDEX OF REFRACTION SQUARED
C  VARIND(I,J)          INDEX OF REFRACTION FOR MATERIAL I AND WAVELENGTH
C                       BIN J
C  VOLVIR               VOLUME FOR VIRTUAL SOURCE
```

```
C  WABS                 CERENKOV WEIGHT ABSORBED IN ZONE
C  WVLNTH(I)           WAVELENGTH BIN I
C                      THESE BINS RUN FROM 1800 TO 5000 ANGSTROMS
C                      IN 200 ANGSTROM WIDE BINS AND THEN FROM
C                      5500 TO 10000 ANGSTROMS IN 500 ANGSTROM BINS
C  WBETA               ELECTRON WEIGHT
C  WNEW                REDUCED WEIGHT OF CERENKOV PHOTON
C  WP                  WEIGHT OF CERENKOV PHOTON
C  WT(J)               TEMPORARY POSITION ARRAY
C  WZERO               INITIAL WEIGHT OF CERENKOV PHOTON
C  XB(J)               TEMPORARY POSITION ARRAY
C  XCHR(J)             PRESENT POSITION
C  XPI(J)              POSITION AT BOUNDARY JUST INSIDE THIS REGION
C  XPO(J)              POSITION AT BOUNDARY JUST INSIDE NEXT REGION
C  XREF                INDEX OF REFRACTION
C  XS                  CURRENT X POSITION (INPUT IN PARAMETER LIST)
C  XVIR                VIRTUAL SOURCE X POSITION
C  YREF                INDEX OF REFRACTION FOR NEXT ZONE
C  YS                  CURRENT Y POSITION (INPUT IN PARAMETER LIST)
C  YVIR                VIRTUAL SOURCE Y POSITION
C  ZE                  CHARGE ON SOURCE PARTICLE IN ELECTRON VOLTS
C  ZS                  CURRENT Z POSITION (INPUT
C                         IN PARAMETER LIST)
C*************************************************************************************
C
*CA CNSTNT
*CA PARAMS
*CA OUT
*CA CALC
*CA PAREM
*CA STTS
*CA GOMLOC
*CA DBG
*CA ORGI
*CA COG
*CA SECZN
      DOUBLE PRECISION DSEED, IRAN
      COMMON /VAXRAN/ IRAN
      DIMENSION C(3),CN(3),CP(3),XCHR(3),XPI(3),XPO(3)
      DIMENSION CDF(20,100),PDF(100)
      DATA PLANKC,ANGTCM/1.2405D-10,1.D-8/
C    RANDOM NUMBER STATEMENT FUNCTION FOR IBM
      RANF(DSEED)= GGUBFS(DSEED)
C  SET CURRENT NUMBER OF MATERIALS WITH DATA FOR INDEX
C  OF REFRACTION IN TABLE ABOVE.
      NMTRLS = 5
C  COUNT THE NUMBER OF TIMES THIS ROUTINE IS CALLED
      NCALL = NCALL + 1
C  SET SOME CONSTANTS
      ALPHA = 1.D0/137.D0
      PI=DACOS(-1.D0)
      TIME=1.D0
      M=1
C  CALCULATE DIRECTION COSINES FOR SOURCE PARTICLE
      C(1) = SPOL*CAZI
      C(2) = SPOL*SAZI
```

```
      C(3) = CPOL
C  SAMPLE RANDOM LOCATION FOR CERENKOV PRODUCTION ALONG A SUBSTEP
      STP = SHD*RANF(IRAN)
C  SET ELECTON LOCATION
      XCHR(1) = XS
      XCHR(2) = YS
      XCHR(3) = ZS
C  PRESENT ZONE OF ELECTRON
      NRC = LBCZ
      NR = IROR(NRC)
      NRMAX = NZON
C  STEP BACK PART WAY ALONG SUBSTEP TO SAMPLE CERENKOV PRODUCTION
      DO 100 J=1,3
         WT(J) = C(J)
         XB(J) = XCHR(J) + C(J)*(STP - SHD)
         XCHR(J) = XB(J)
100   CONTINUE
C  FIND ZONE OF CERENKOV PRODUCTION AND COMPUTE UNCOLLIDED
C  ESCAPE DISTANCE.
      CALL ZONEA
C
C  NEXT ZONE TO BE ENCOUNTERED BY CERENKOV RAY.
      NRC=IRPRIM
C  PRESENT ZONE OF CERENKOV PRODUCTION
      NR=IR
C  WHAT MATERIAL IS ELECTRON IN FOR CERENKOV PRODUCTION?
      MTRL=IDINT(CHER(1,NR))
C  GET THE INDEX OF REFRACTION FOR THAT MATERIAL
      XREF=VARIND(MTRL,27)
C *** CALCULATE VELOCITY OF SOURCE PARTICLE ***
C  ELECTRON ENERGY NORMALIZED TO REST MASS ENERGY
C  TOTAL ENERGY = KINETIC ENERGY + REST MASS ENERGY (EE = GAMA)
      EE = 1.D0 + EBETA/.511D0
C  NORMALIZED VELOCITY (V2 = BETA SQUARED)
      V2 = 1.D0 - 1.D0/(EE*EE)
C  (V = BETA)
      V = DSQRT(V2)
C  (BETA SQUARED * INDEX OF REFRACTION SQUARED)
      V2N2 = V2*XREF*XREF
C  CALCULATE THE CDF FOR ALL THE MATERIALS AVAILABLE
      IF(NCALL .EQ. 1) THEN
         CALL CKVCDF(V,NMTRLS,VARIND,WVLNTH,CDF)
      ENDIF
C *** DOES PARTICLE MEET CERENKOV THRESHOLD ***
      IF(XREF .LE. 1.D0) GO TO 1600
      IF(V2N2 .LE. 1.D0) GO TO 1600
C  THE CERENKOV PHOTON WEIGHT TO BE USED IS THE TOTAL INTEGRATED
C  WEIGHT OVER THE ENTIRE RANGE OF WAVELENGTHS AND FOR THE
C  ENTIRE LENGTH OF THE SUBSTEP
      WP = 0.D0
      DO 150 I=2,NMBINS
         WP = 2.D0*PI*ALPHA*SHD*WBETA*DABS((1.D0/(ANGTCM*WVLNTH(I-1))
     1   - 1.D0/(ANGTCM*WVLNTH(I)))*
     2   (1.D0-1.D0/V/V/VARIND(MTRL,I-1)/VARIND(MTRL,I-1)))
     3   + WP
```

```
 150  CONTINUE
C  SAMPLE TO GET CORRECT CERENKOV BIN
      CALL CKVWVL(CDF,MTRL,NCBIN)
C *** GET INDEX OF REFRACTION ***
      XREF = VARIND(MTRL,NCBIN)
C *** IS INDEX OF REFRACTION ABOVE CUTOFF FOR CERENKOV? ***
      IF(XREF .LE. 1.D0) GO TO 1600
C  CALCULATE PHOTON ENERGY
      EP = PLANKC/(ANGTCM*WVLNTH(NCBIN))
C *** CALCULATE COSINE FOR CERENKOV PHOTON IN MOVING FRAME
C ***    = 1 / (BETA * INDEX OF REFRACTION)
C ***    = RATIO OF SPEED OF LIGHT IN MEDIUM TO ELECTRON VELOCITY
      CPRO = 1.D0/(V*XREF)
C *** TALLY PHOTON NUMBER COUNT, WEIGHT, AND ENERGY PRODUCED HERE
      CHRNUM(NR,NCBIN) = CHRNUM(NR,NCBIN) + 1.D0
      CHRWAT(NR,NCBIN) = CHRWAT(NR,NCBIN) + WP
      CHRENG(NR,NCBIN) = CHRENG(NR,NCBIN) + EP*WP
C *** BRING POLAR ANGLE BACK INTO LAB FRAME ***
      CALL FOLD(CPOL,SPOL,CAZI,SAZI,CPRO,CZ,SZ,CX,SX)
C *** USE SAME INITIAL PHOTON WEIGHT
      WZERO = WP
C *** SET DIRECTION COSINES AND PREPARE FOR RAY TRACE ***
      C(1) = SZ*CX
      C(2) = SZ*SX
      C(3) = CZ
C *** CONDUCT RAY TRACE OF CERENKOV PHOTON THROUGH GEOMETRY ***
      NUMCT = NUMCT + 1
C  SET INITIAL COLLISTION COUNTER
      KLIDE = 0
C *** NR, PRESENT (USER) REGION
C *** NRC, PRESENT (CODE) REGION
C *** NRPC, NEXT (CODE) REGION
C *** X, PRESENT POSITION OF CERENKOV RAY
C *** C, PRESENT DIRECTION OF CERENKOV RAY
C *** ST, DISTANCE TO BOUNDARY
C *** NRP, NEXT (USER) REGION
C *** NSC, SURFACE ENCOUNTERED BY RAY
C *** XPI, POSITION OF RAY AT BOUNDARY JUST INSIDE THIS REGION
C *** XPI, POSITION OF RAY AT BOUNDARY JUST INSIDE THE NEXT REGION
C *** CN, NORMAL DIRECTION FROM THIS REGION TOWARD NEXT REGION
700   CALL PATH(NR,NRC,XCHR,C,ST,NRPC,NSC,XPI,XPO,CN)
C *** CHECK FORMATTING HERE ***
C *** IF NO ZONE IS FOUND THEN PHOTON ESCAPES
      IF(IRPRIM .LT. 0) THEN
         M = 5
         GO TO 1600
      ENDIF
      M = 3
C *** COMPUTE THE PHOTON WEIGHT ATTENUATION AND DETERMINE THE WEIGHT
C *** LEFT FOR FURTHER RAY TRACE.
      WNEW = WP*DEXP(-ST*CHER(2,NR))
C *** UPDATE THE WEIGHT (CALCULATE THE WEIGHT ABSORBED IN ZONE)
      WABS = WP - WNEW
      WP = WNEW
C *** TALLY THE ABSORBED WEIGHT FOR THAT ZONE
```

```
      CHRABS(NR,NCBIN) = CHRABS(NR,NCBIN) + WABS
C *** THIS SECTION CREATES TALLIES FOR VIRTUAL SOURCE
      IF(IVIRS .EQ. 1) THEN
         ICVIR = IBFIND(C(3),NCVIR,CVIRB)
         IF(ICVIR .LE. 0) GO TO 1000
         SVIR = (HVIR - XCHR(3))/C(3)
         XVIR = XCHR(1) + SVIR*C(1)
         YVIR = XCHR(2) + SVIR*C(2)
         RVIR = DSQRT(XVIR*XVIR + YVIR*YVIR)
         IRVIR = IBFIND(RVIR,NRVIR,RVIRB)
         IF(IRVIR .LE. 0) GO TO 1000
         CTVIR = 1.D0
         STVIR = 0.D0
         IF(RVIR .GT. 0.D0) THEN
            CTVIR = XVIR/RVIR
            STVIR = YVIR/RVIR
         ENDIF
         AVIR = 0.D0
         CSQ = DSQRT(C(1)*C(1) + C(2)*C(2))
         IF(CSQ .LE. 0.D0) GO TO 900
         AVIR = (CTVIR*C(1) + STVIR*C(2))/CSQ
         IF(DABS(AVIR) .GT. 1.D0) AVIR = AVIR/DABS(AVIR)
         AVIR = DACOS(AVIR)
900      IAVIR = IBFIND(AVIR,NAVIR,AVIRB)
         IF(IAVIR .LE. 0) GO TO 1000
         VOLVIR = 2.D0*PI*(RVIRB(IRVIR + 1)**2-RVIRB(IRVIR)**2)
     1      *(CVIRB(ICVIR + 1) - CVIRB(ICVIR))
     2      *(AVIRB(IAVIR + 1) - AVIRB(IAVIR))
         SCOVOL(IAVIR,ICVIR,IRVIR)=SCOVOL(IAVIR,ICVIR,IRVIR)+WP/VOLVIR
      ENDIF
C*************** END OF VIRTUAL SOURCE SECTION ******************
C *** INCREMENT THE NUMBER OF REFLECTIONS (COLLISIONS OF PHOTON)
1000  KLIDE = KLIDE + 1
C *** PUT AN UPPER LIMIT ON THE NUMBER OF REFLECTIONS ALLOWED
C ***    (IE. DON'T GET IN AN INFINITE LOOP BETWEEN WALLS)
      IF((KLIDE .GT. KALTOT) .OR. (WP .LT. WZERO*1.D-3)) THEN
         WKILL = WKILL + WP
         GO TO 1600
      ENDIF
C *** INITIALIZE SPECULAR AND DIFFUSE REFLECTION COEFFICIENTS
      SPECU = 0.D0
      DIFFU = 0.D0
C *** SET NEXT REGION THAT RAY WILL PASS INTO
      NRP = NRPC
C *** CHECK TO SEE IF WE HAVE A NEXT REGION
C *** IF SO THEN GET THE TRUE SPECULAR AND DIFFUSE COEFFICIENTS
      IF(NRPC .GT. 0) NRP=IROR(NRPC)
      IF(NRP .GT. 0) THEN
         SPECU = CHER(3,NRP)
         DIFFU = CHER(4,NRP)
      ENDIF
C *** CHECK TO SEE IF PHOTON UNDERGOES SPECULAR OR DIFFUSE REFLECTION
      RA = RANF(IRAN)-SPECU
      IF(RA .LE. 0.D0) THEN
C *** SPECULAR REFLECTION ***
```

```
         CPRE = C(1)*CN(1) + C(2)*CN(2) + C(3)*CN(3)
1100     PSI = 2.D0*CPRE
C *** NEW DIRECTION = OLD DIRECTION - 2*(NORMAL COMPONENT)
C ***     VECTR2 = VECTR1 - 2*(NMLVECT DOT VECTR1)*NMLVECT
         C(1) = C(1) - PSI*CN(1)
         C(2) = C(2) - PSI*CN(2)
         C(3) = C(3) - PSI*CN(3)
C *** SET NEW POSITION OF THE RAY
         DO 1200 J=1,3
            XCHR(J) = XPI(J)
1200     CONTINUE
C *** GO BACK TO PATH AND FOLLOW THE RAY THROUGH THIS NEXT ZONE
         GO TO 700
      ENDIF
C *** CHECK FOR DIFFUSE REFLECTION ***
      RA = RA - DIFFU
      IF(RA .LE. 0.D0) THEN
C *** SAMPLE RANDOM POLAR COSINE RELATIVE TO SURFACE NORMAL
         CP(3) = -RANF(IRAN)
C *** SINE OF POLAR SCATTERING ANGLE
         SINE = DSQRT(1.D0 - CP(3)*CP(3))
C *** AZIMUTHAL SCATTERING ANGLE RANDOM BETWEEN + OR - PI
         THE = PI*(2.D0*RANF(IRAN) - 1.D0)
         CP(1) = SINE*DCOS(THE)
         CP(2) = SINE*DSIN(THE)
C *** ROTATE DIRECTION COSINES BACK INTO LAB FRAME
         CALL ROTCPC(CN,CP,C)
C *** UPDATE CURRENT POSITION OF THE RAY
         DO 1300 J=1,3
            XCHR(J) = XPI(J)
1300     CONTINUE
C *** GO BACK TO PATH AND RAY TRACE THROUGH THE NEXT ZONE
         GO TO 700
      ENDIF
C *** IF THERE IS NO REFLECTION, TRANSMIT THE CERENKOV PHOTON ***
C *** SET COSINE OF INCOMING RAY RELATIVE TO SURFACE NORMAL
      CPRE = C(1)*CN(1) + C(2)*CN(2) +C(3)*CN(3)
      YREF = 1.D0
C *** SET ZONE NUMBER TO THAT OF THE ZONE THE RAY IS ENTERING
      NRP = NRPC
      IF(NRPC .GT. 0) NRP=IROR(NRPC)
      ACCEPT = 1.D0
C *** IF THERE IS A NEXT ZONE SET INDEX OF REFRACTION AND FRACTION
C *** ACCEPTED
      IF(NRP .GT. 0) THEN
         MTRL1 = IDINT(CHER(1,NRP))
         YREF = VARIND(MTRL1,NCBIN)
         ACCEPT = CHER(5,NRP)
      ENDIF
C *** TEST TO SEE IF THE PHOTON IS REFLECTED OR TRANSMITTED
      IF(RANF(IRAN) .GT. ACCEPT) GO TO 1100
C *** DOES SNELLS LAW ALLOW TRANSMITION? (SNELL'S LAW IN TERMS OF
C *** COSINE OF ANGLE SQUARED)
      CP2 = 1.D0 - XREF*XREF*(1.D0 - CPRE*CPRE)/(YREF*YREF)
C *** IF COSINE OF ANGLE SQUARED LESS THAN OR EQUAL ZERO THEN
C *** SPECULAR REFLECTION OCCURS (OUTSIDE CRITICAL ANGLE)
```

```
      IF(CP2 .LE. 0.D0) GO TO 1100
      SPRE = DSQRT(1.D0 - CPRE*CPRE)
      CAFT = DSQRT(CP2)
      SAFT = DSQRT(1.D0 - CP2)
      SRAT = SAFT/SPRE
      CRAT = CAFT - SRAT*CPRE
C *** DIRECTION COSINES OF RAY AFTER ENTERING NEW ZONE IN LAB FRAME
      DO 1400 J=1,3
         C(J) = SRAT*C(J) + CRAT*CN(J)
1400  CONTINUE
C *** INCREMENT CERENKOV WEIGHT EXITING PREVIOUS ZONE
      CHROUT(NR,NCBIN) = CHROUT(NR,NCBIN) + WP
C *** IS THERE A NEXT ZONE?
      IF(NRP .GE. 0) THEN
C *** INCREMENT CERENKOV WEIGHT ENTERING NEXT ZONE
         CHRENT(NRP,NCBIN) = CHRENT(NRP,NCBIN) + WP
C *** UPDATE ZONE AND INDEX OF REFRACTION
         NR = NRP
         NRC = NRPC
         XREF = YREF
C *** SET RAY POSITION JUST INSIDE NEXT ZONE BOUNDARY
         DO 1500 J=1,3
            XCHR(J) = XPO(J)
1500     CONTINUE
C *** GO BACK TO PATH AND FOLLOW THE RAY THROUGH THIS NEXT ZONE
         IF(NRP .LT. NRMAX) GO TO 700
      ENDIF
 1600 RETURN
      END
C *** SUBROUTINE TO ROTATE COORDINATES BACK INTO LAB FRAME
      SUBROUTINE ROTCPC(CP,D,C)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION CP(3),D(3),C(3),E3(3),E2(3),E1(3)
      DO 100 J=1,3
         E3(J) = CP(J)
100   CONTINUE
      E22 = E3(1)*E3(1) + E3(2)*E3(2)
      IF(E22 .LE. 0.D0) THEN
         E2(1) = 1.D0
         E2(2) = 0.D0
      ELSE
         E22 = DSQRT(E22)
         E2(1) = -E3(2)/E22
         E2(2) = E3(1)/E22
      ENDIF
      E2(3) = 0.D0
      E1(1) = E2(2)*E3(3) - E2(3)*E3(2)
      E1(2) = E2(3)*E3(1) - E2(1)*E3(3)
      E1(3) = E2(1)*E3(2) - E2(2)*E3(1)
      DO 200 J=1,3
         C(J) = D(1)*E1(J) + D(2)*E2(J) + D(3)*E3(J)
200   CONTINUE
      RETURN
      END
      SUBROUTINE PATH(NR,NRG,X,C,ST,NRGP,NSCP,XPI,XPO,CN)
C *** RAY TRACING SUBROUTINE ****
```

```
*CA CNSTNT
*CA PARAMS
*CA PAREM
*CA STTS
*CA GOMLOC
*CA DBG
*CA ORGI
*CA SECZN
*CA COG
      COMMON/NRML/UN(3)
      DIMENSION X(3),C(3),XPO(3),XPI(3),CN(3)
C *** ACCEPT VERSION
      DIST = CZERO
      DISTO = PINF
      IRPRIM = NRG
      IR = NR
      KLOOP = KLOOP + 1
      DO 100 I=1,3
         XB(I)=X(I)
         WT(I)=C(I)
100   CONTINUE
      ICALL = 0
      IZE = 0
      CALL DISTA(S)
      IF(IRPRIM .GE. 0) THEN
         ST = DIST
         DO 200 I=1,3
            XPI(I) = X(I) + (ST*0.99999D0)*C(I)
            XPO(I) = X(I) + (ST*1.00001D0)*C(I)
200      CONTINUE
         NRGP = IRPRIM
         NSCP = LSURF
         CALL NORML(NRG,LSAVE)
C *** SET NORMAL TO DIRECTION UNTIL NORMAL IS AVAILABLE
         DO 300 I=1,3
            CN(I) = -UN(I)
300      CONTINUE
      ENDIF
      RETURN
      END
       SUBROUTINE NORML(IRR,NASC)
C *** USER BEWARE:  MUCH OF THIS ROUTINE IS UNTESTED.  IT IS ASSUMED
C *** THAT XB+WT*DIST IS ON SURFACE LSURF OF BODY NASC.  THUS A NORMAL
C *** CALL MUST BE PROCEEDED BY A CALL TO G1 OR LOOKZ.
*CA CNSTNT
*CA PARAMS
*CA PAREM
*CA GOMLOC
*CA DBG
*CA ORGI
*CA SECZN
*CA COG
      COMMON /NRML/UN(3)
      DIMENSION XP(3),WP(3),X(3),H(3),IBOX1(3),IBOX2(3)
      DATA IBOX1/10,7,4/
      DATA IBOX2/4,10,7/
```

```
      LSUR = IABS(LSURF)
      DO 100 I=1,3
         XP(I) = XB(I) + DIST*WT(I)
100   CONTINUE
      N = LOCREG(IRR)
      NUM = NUMBOD(IRR)*4 + N - 4
      DO 200 I=N,NUM,4
         IF(NASC .EQ. I) GO TO 400
200   CONTINUE
      WRITE(6,300) IRR,NASC,(MA(I),I=N,NUM,4)
300   FORMAT(1X,'INVALID REGION OR BODY IN NORMAL.    IR =',I7,'NASC=',
     1   I7,/,(10I7))
      CALL PR(1)
      STOP
400   L = MA(I+1)
      ITYPE = MA(L+1)
      K = MA(L+4)
C            ARB  SPH  RCC  REC  TRC  ELL  BOX  WED  RPP
      GO TO (500,1200,1400,1500,1400,1600,1700,1500,1900), ITYPE
C *** ARB
500   I=K + 1 + 4*(LSUR - 1)
      DO 1110 J=1,3
         UN(J) = FPD(I+J)
1110  CONTINUE
      GO TO 2000
C *** SPH
1200  DO 1210 I=1,3
         UN(I) = (XP(I) - FPD(K+I+1))/FPD(K+5)
1210  CONTINUE
      GO TO 2000
C *** TRC AND RCC
1400  H2=0.D0
      DO 1410 I=1,3
         H(I)=FPD(K+4+I)
         H2=H2 + H(I)*H(I)
1410  CONTINUE
      GO TO (1415,1415,1435), LSUR
1415  H2 = DSQRT(H2)
      DO 1420 I=1,3
         UN(I) = H(I)/H2
1420  CONTINUE
      GO TO 2000
1435  DO 1440 I=1,3
         X(I) = XP(I) - FPD(K+1+I)
1440  CONTINUE
      XMU = 0.D0
      A2 = 0.D0
      DO 1445 I=1,3
         J = MOD(I,3) + 1
         A2 = A2 + (H(I)*X(J) - H(J)*X(I))**2
         XMU = XMU + FPD(K+4+I)*X(I)
1445  CONTINUE
      R = FPD(K+8) - FPD(K+9)
      IF(ITYPE .EQ. 3) R = 0.D0
      B1 = R/DSQRT(H2*(H2 + R*R))
      B2 = 1.D0/DSQRT(A2*(H2 + R*R))
```

```
      DO 1450 I=1,3
         UN(I) = B2*(X(I)*H2 - H(I)*XMU) + B1*H(I)
1450  CONTINUE
      GO TO 2000
1500  WRITE(6,1501) ITYPE
1501  FORMAT(1X,'NOT IMPLEMENTED IN NORMAL.  ITYPE =',I5)
      STOP
C *** ELL
1600  DX = 0.D0
      AN = 0.D0
      C2 = FPD(K+8)**2/4.D0
      DO 1620 I=1,3
         IA = I + K + 1
         X(I) = XP(I) - .5D0*(FPD(IA) + FPD(IA+3))
         H(I) = .5D0*(FPD(IA+3) - FPD(IA))
         DX = DX + X(I)*H(I)
1620  CONTINUE
      DO 1630 I=1,3
         UN(I) = C2*X(I) - DX*H(I)
         AN = AN + UN(I)*UN(I)
1630  CONTINUE
      IF(AN .GE. 1.D-12) THEN
         AN = DSQRT(AN)
         DO 1635 I=1,3
            UN(I) = UN(I)/AN
1635     CONTINUE
         GO TO 2000
      ENDIF
1650  WRITE(6,1651) NBO,LSURF,(XP(I),I=1,3)
1651  FORMAT(1X,'ROUND-OFF ERROR IN NORMAL.  NBO=',I5,'LSURF=',I5,
     1   'XP=',3E12.5)
      STOP
C *** BOX
1700  L = 1 + (LSUR - 1)/2
      I1 = IBOX1(L)
      I2 = IBOX2(L)
      DO 1720 I=1,3
         X(I) = FPD(K+I1+I)
         H(I) = FPD(K+I2+I)
1720  CONTINUE
      AN = 0.D0
      DO 1730 I=1,3
         J = MOD(I,3) + 1
         JJ = MOD(I+1,3) + 1
         UN(I) = X(J)*H(JJ) - X(JJ)*H(J)
         AN = AN + UN(I)*UN(I)
1730  CONTINUE
      IF(AN .LT. 1.0D-12) GO TO 1650
      AN = DSQRT(AN)
      DO 1735 I=1,3
         UN(I) = UN(I)/AN
1735  CONTINUE
      GO TO 2000
C *** RPP
1900  DO 1905 I=1,3
```

```
         UN(I) = 0.D0
1905  CONTINUE
      GO TO (1910,1910,1920,1920,1930,1930), LSUR
1910  UN(2) = 1.D0
      GO TO 2000
1920  UN(1) = 1.D0
      GO TO 2000
1930  UN(3) = 1.D0
2000  XMU = 0.D0
      DO 2005 I=1,3
         XMU = XMU + WT(I)*UN(I)
2005  CONTINUE
      XMU = -1.D0*XMU
C     AN = SIGN(1.D0, XMU)
      IF(XMU .LT. 0.D0) THEN
         AN = -1.D0
      ELSE
         AN = 1.D0
      ENDIF
      XMU = -1.D0*XMU
      DO 2010 I=1,3
         UN(I) = AN*UN(I)
2010  CONTINUE
      RETURN
      END
      FUNCTION IBFIND(X,MX,XB)
C *** IBFIND FINDS CORRECT TALLY BINS ***
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION XB(100)
      IBFIND=0
      IF(X .LT. XB(1)) GO TO 7777
      DO 1000 I=1,MX
         IF(X .LE. XB(I+1))  GO TO 1010
1000  CONTINUE
      GO TO 7777
1010  IBFIND=I
7777  RETURN
      END
      SUBROUTINE CKVCDF(BETA,NMTRLS,VARIND,WVLNTH,CDF)
C
C  THIS SUBROUTINE CREATES A TABLE OF INDEX OF REFRACTION VS
C  FREQUENCY VALUES AND BUILDS THE CDF FOR CERENKOV PRODUCTION
C  BY WAVELENGTH.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      INTEGER I,N,MTRL,NMTRLS
      DIMENSION WVLNTH(100),CDF(20,100),VARIND(100,100),PDF(100)
C  ASSIGN VALUES TO CONSTANTS
      N = 27
      PI = DACOS(-1.D0)
      ALPHA = 1.D0/137.D0
C  CALCULATE THE NUMBER OF CERENKOV PHOTONS PER PATH LENGTH PRODUCED
C     FOR EACH WAVELENGTH INTERVAL.  ALSO CALCULATE THE TOTAL NUMBER
C     OF PHOTONS PRODUCED PER PATH LENGTH
      DO 450 MTRL=1,NMTRLS
        PTOT = 0.D0
```

```
        DO 200 I=2,N
           PDF(I-1) = 2.D0*PI*ALPHA*DABS((1.D0/WVLNTH(I-1)
     1        - 1.D0/WVLNTH(I))*
     2        (1.D0-1.D0/BETA/BETA/VARIND(MTRL,I-1)/VARIND(MTRL,I-1)))
           PTOT = PTOT + PDF(I-1)
200     CONTINUE
C NORMALIZE PDF
        DO 300 I=1,N-1
           PDF(I) = PDF(I)/PTOT
300     CONTINUE
C  CREATE CDF TABLE
           CDF(MTRL,1) = PDF(1)
        DO 350 I=2,N-1
           CDF(MTRL,I) = CDF(MTRL,I-1) + PDF(I)
350     CONTINUE
450   CONTINUE
      RETURN
      END
      SUBROUTINE CKVWVL(CDF,MTRL,NCBIN)
C
C  THIS SUBROUTINE SAMPLES THE WAVELENGTH OF THE EMITTED CERENKOV
C  PHOTON AND RETURNS THE BIN NUMBER IN NCBIN.  IT REQUIRES INPUT
C  OF THE ARRAYS WVLNTH AND CDF WHICH MUST BE OBTAINED
C  BY A PREVIOUS CALL TO CKVCDF.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      INTEGER I,NCBIN,NBINS,MTRL
      DIMENSION CDF(20,100)
      DOUBLE PRECISION DSEED, IRAN
      COMMON /VAXRAN/ IRAN
C  GET RANDOM VARIABLE
      RANF(DSEED) = GGUBFS(DSEED)
      RND1 = RANF(IRAN)
C  RANDOMLY SAMPLE THE CDF FOR CERENKOV RADIATION AND DETERMINE
C  THE BIN NUMBER OF THE SAMPLED CERENKOV PHOTON
      NBINS = 27-1
      DO 100 I=1,NBINS
         IF(RND1 .LE. CDF(MTRL,I)) THEN
            NCBIN = I
            GO TO 200
         ENDIF
100   CONTINUE
 200  RETURN
      END
```

APPENDIX D. SAMPLE CROSS SECTION INPUT FILE

```
ENERGY 17.
MATERIAL AL
MATERIAL FE
MATERIAL C .2729 O .7271
  GAS
  DENSITY .003986
MATERIAL SI .4675 O .5325 DENSITY 2.5
MATERIAL PB
TITLE
 .....ITS(KEY,ACCEPT) TEST CERENKOV 89.....
```

APPENDIX E. SAMPLE CERENKOV INPUT FILE WITH GEOMETRY AND ZONE DESCRIPTIONS

```
ECHO 1
TITLE
  TEST CERENKOV 89
ELECTRONS
ENERGY 16.7
POSITION 0.0 0.0 0.0
DIRECTION 0.0 0.0
HISTORIES 10000
CUTOFFS .06819 .06819
ELECTRON-ESCAPE
  NBINE 10
  NBINT 10
PHOTON-ESCAPE
  NBINE 10
  NBINT 10
ELECTRON-FLUX 9 18 NBINE 20
PHOTON-FLUX 9 18 NBINE 20
GEOMETRY
  RCC    0.0       0.0      -1.0       0.0       0.0       1.0
         6.35
  RCC    0.0       0.0       0.0       0.0       0.0       0.0508
         3.81
  RCC    0.0       0.0       0.0508    0.0       0.0       0.635
         3.81
  RCC    0.0       0.0       0.6858    0.0       0.0       0.00762
         3.81
  RCC    0.0       0.0       0.0       0.0       0.0       51.11
         6.35
  RCC    0.0       0.0       0.0       0.0       0.0       51.11
         6.1134
  RCC    0.0       0.0      38.01842  -0.00113   0.0       0.001130
         6.0
  RCC    0.0       0.0      51.11      0.0       0.0       3.0
         6.35
  RCC    0.0       0.0      38.01842  36.744     0.0       0.0
         6.1134
  RCC    0.0       0.0      38.01842  36.744     0.0       0.0
         6.35
  RCC   26.584     0.0      38.01842   0.0       0.0      13.785
         6.1134
  RCC   26.584     0.0      38.01842   0.0       0.0      13.785
         6.35
  SPH   28.716     0.0      38.01842   9.49
  RCC   18.504     0.0      38.01842   3.0       0.0       0.0
         4.95
  RCC   26.584     0.0      38.01842   0.00113   0.0      -0.00113
         6.0
  RCC   26.584     0.0      51.80342   0.0       0.0       0.318
         3.81
```

```
  END
   Z1    +1
   Z2    +2
   Z3    +3
   Z4    +4
   Z5    +6    -2    -3    -4    -7
   Z6    +7
   Z7    +8
   Z8    +5    -6    -9
   Z9    +9    +5    -6
  Z10    +10   -5    -9    -11
  Z11    +9    -5    -14   -15
  Z12    +12   -10   -1    -2    -3    -11
  Z13    +11   -10
  Z14    +13   +14
  Z15    +14   -13
  Z16    +10   +11   -9
  Z17    +15
  Z18    +16
  Z19    -1    -5    -8    -10   -12   -16
  END
* MAT ECUT PTCZ
 0
 1 0 .1
 0
 2
 3
 4
 0
 2 12.0
 0
 2 12.0
 0
 2 12.0
 0
 4
 0
 0
 4
 4
 0
*  The two values immediately following the key word, CERENKOV, allow
*  the user to set the pressure of air or carbon dioxide gas
*  within the geometry, and the temperature in kelvin.
*  (Other gasses are not included in the current version.)
*  The pressure in units of standard atmospheres.
*  Once set, the pressure applies to all of that type of gas
*  throughout the geometry.  The temperature applies to all gasses.
*  The code uses these values to scale the indices of refraction
*  for air and carbon dioxide.
*  (The user is still required to generate the appropriate
*  cross section tape for the gasses at these new densities.)
*           AIRP    CO2P      temp     kaltot
*           (atm)   (atm)   (kelvin)
CERENKOV    1.00    2.00      293.0      15
* The material number below is not the same as the material number
```

```
* used above in the MAT section.  Instead it refers to
* materials for which the Cerenkov
* subroutine has index of refraction data.  These are currently:
*       1  --  Vacuum
*       2  --  Air
*       3  --  Carbon Dioxide
*       4  --  Glass
*       5  --  Crystal Quartz
* Note that Vacuum is used whenever we want to set the index of
* refraction to a value of 1.0.
*     MATERIAL       LAMBDA         MIRROR         DIFFUSE        ACCEPT
          1            0.0            0.0            0.0            1.0
          1         1000.0            0.0            0.0            1.0
          1            0.0            0.0            0.0            1.0
          1         1000.0            0.0            0.0            1.0
          3            0.0            0.0            0.0            1.0
          4            0.05           0.9            0.0            0.0
          1            0.0            0.0            0.0            1.0
          1         1000.0            0.0            1.0            0.0
          1            0.0            0.0            0.0            1.0
          1         1000.0            0.0            1.0            0.0
          1            0.0            0.0            0.0            1.0
          1         1000.0            0.0            1.0            0.0
          1            0.0            0.0            0.0            1.0
          4            0.0            0.0            0.0            1.0
          1            0.0            0.0            0.0            1.0
          1            0.0            0.0            0.0            1.0
          4            0.05           0.9            0.0            0.0
          1         1000.0            0.0            0.0            1.0
          1            0.0            0.0            0.0            1.0
* AL 20MIL 29.3P 16.7MEV 400K HIST T11X20 KLIDE 15
```

A. PROBLEM GEOMETRY

To describe the geometry of an object in ACCEPT the user must execute four distinct tasks: [Ref. 11: p. 73]

1. Define the location and orientation of each solid geometrical body required for specifying the input zones.
2. Specify the input zones as combinations of these bodies.
3. Specify the volumes of the input zones, if necessary.
4. Specify the material in each input zone.

The use of combinatorial geometry is based upon a library of geometrical body types from which the user chooses a specific combination to describe the body he is modelling. These figures are shown on the following pages. [Ref. 11: pp. 74-82]

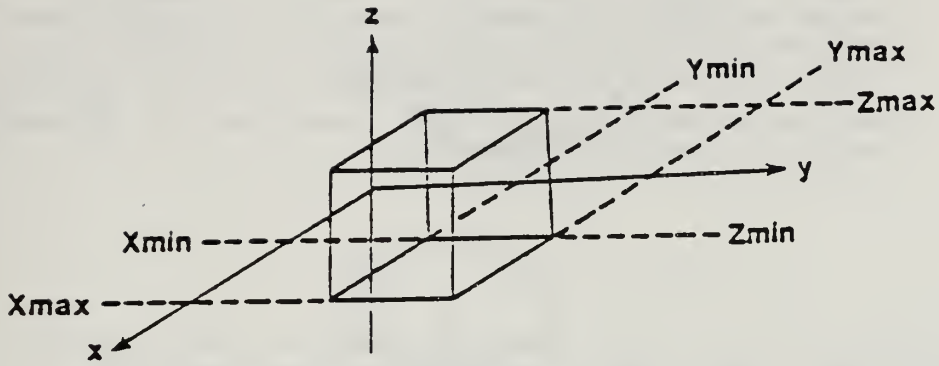


Figure E-1: Rectangular Parallelepiped (RPP)

b) Sphere (SPH) -- Specify the components of the radius vector $\underline{V}$ to the center of the sphere and the radius R of the sphere.

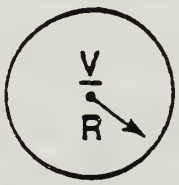


Figure E-2: Sphere (SPH)

c) Right Circular Cylinder (RCC) -- Specify the components of a radius vector $\underline{V}$ to the center of one base, the components of a vector $\underline{H}$ from the center of that base to the center of the other base, and the radius R of the cylinder.

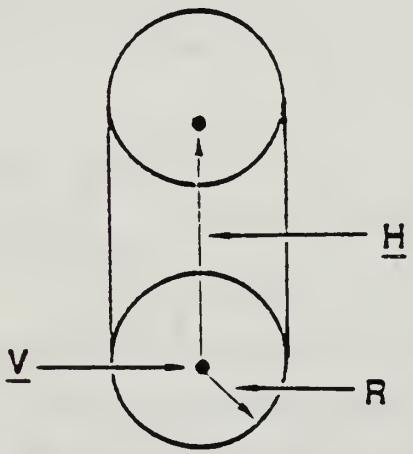


Figure E-3: Right Circular Cylinder (RCC)

d) Right Elliptical Cylinder (REC) -- Specify the components of a radius vector $\underline{V}$ to the center of one of the elliptical bases, the components of a vector $\underline{H}$ from the center of that base to the center of the other base, and the components of two vectors $\underline{R_1}$ and $\underline{R_2}$ defining the major and minor axes, respectively, of the bases. This body has not yet been implemented.

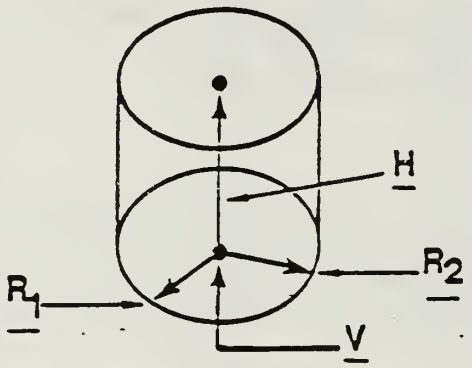


Figure E-4: Right Elliptical Cylinder (REC)

e) Truncated Right Angle Cone (TRC) -- Specify the components of a radius vector $\underline{V}$ to the center of one base, the components of a vector $\underline{H}$ from the center of that base to the center of the other base, and the radii R_1 and R_2 of the first and second bases, respectively.

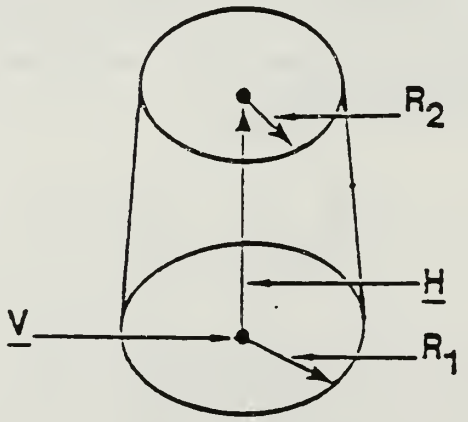


Figure E-5: Truncated Right Angular Cone (TRC)

f) Ellipsoid (ELL) -- Specify the components of the radius vectors $\underline{V_1}$ and $\underline{V_2}$ to the foci of the prolate ellipsoid and the length of the major axis R.

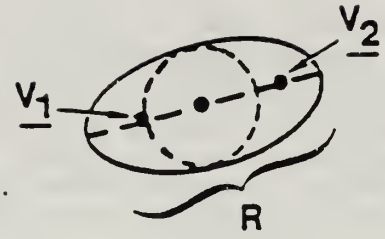


Figure E-6: Ellipsoid (ELL)

g) Wedge (WED) -- Specify the components of a radius vector $\underline{V}$ to one of the corners and the components of three mutually perpendicular vectors $\underline{a}_1$, $\underline{a}_2$ and $\underline{a}_3$ starting at that corner and defining the wedge such that $\underline{a}_1$ and $\underline{a}_2$ are the two legs of the right triangle of the wedge.

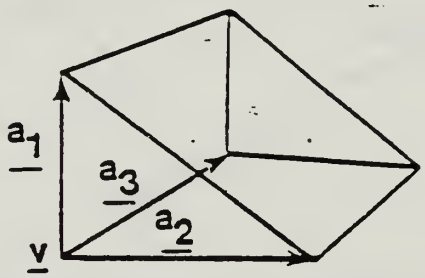


Figure E-7: Right Angle Wedge (WED)

h) Box (BOX) -- Specify the components of a radius vector $\underline{V}$ to one of the corners and the components of three mutually perpendicular vectors $\underline{a}_1$, $\underline{a}_2$ and $\underline{a}_3$ starting at that corner and defining a rectangular parallelepiped of arbitrary orientation.

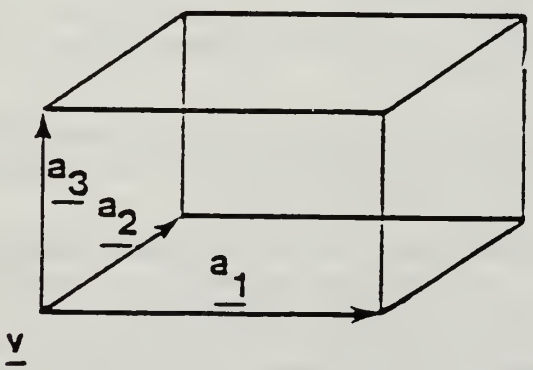


Figure E-8: Box (BOX)

i) Arbitrary Polyhedron (ARB) -- Specify the components of k (k = 5, 7 or 8) radius vectors, $\underline{V_1}$ through $\underline{V_k}$, to the corners of an arbitrary nonreentrant polyhedron of up to six sides, and specify the indices of the corners of each face by means of a series of four-digit floating point numbers between "1230." and "8765." (enter zero for the fourth index of a three-cornered face). These indices must appear in either clockwise or counterclockwise order.

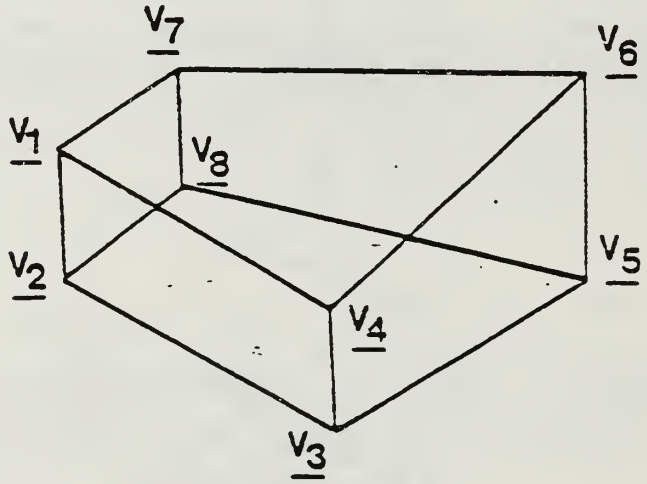


Figure E-9: Arbitrary Polyhedron (ARB)

E.1.2 Specification of Input Zones -- Having defined the necessary geometrical bodies, the user must then resolve the entire problem geometry into input zones satisfying the following criteria:

a) An input zone may consist only of either a single homogeneous material or a void.

b) Every point of the problem geometry must lie within one and only one input zone.

c) The final input zone must be a non-reentrant void zone surrounding the rest of the problem geometry; any particle entering this zone is tallied as an escape particle.

Input zones are specified as appropriate combinations of the previously defined bodies. Such combinations may be as simple as just a single body, or they may consist of complex intersections, unions and differences of various bodies. We illustrate the principles of input zone specification with the following examples where, for simplicity, we omit the escape zone. Each example involves only two zones, A and B, defined by the cross-hatching in Fig. E-10.

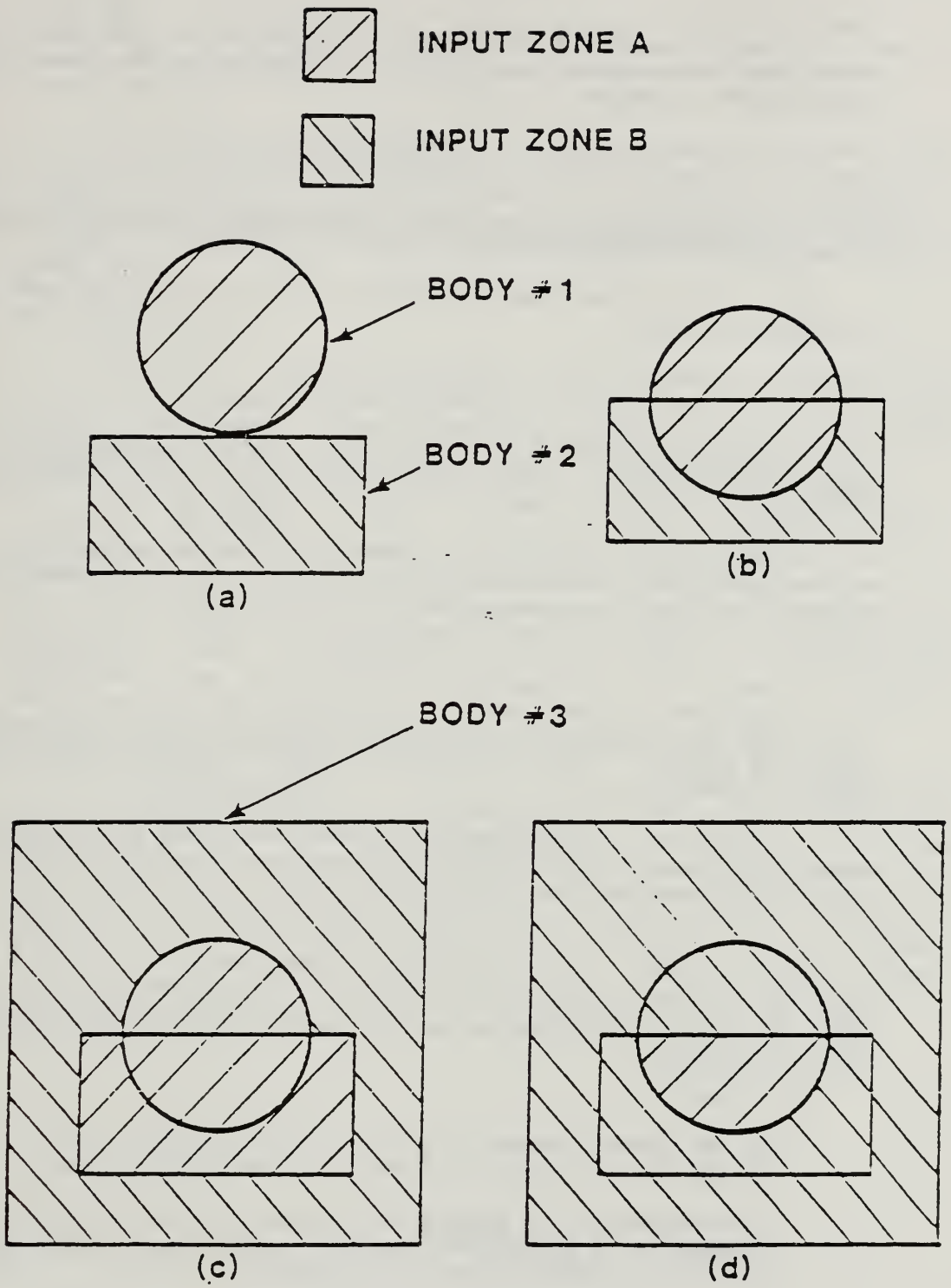


Figure B-10: Illustration of Various Methods of Combining Bodies for Specification of Input Zones.

In Fig. E-10a, zone A consists of a sphere, body #1, that is tangent to zone B which consists of a right circular cylinder, body #2. Input zone specification is simply

A = +1
and B = +2 .

That is, input zone A consists of all spatial points that lie within body #1, and similarly for zone B.

In Fig. E-10b, the sphere is inserted into a hole that has been cut in the cylinder so that

A = +1
and B = +2 -1 .

Thus, input zone B consists of all spatial points that lie within body #2 AND not within body #1. Input zone B is specified as the difference between two bodies.

In Fig. E-10c, bodies #1 and #2 consist of the same homogeneous material (or void), but they are imbedded within a second right circular cylinder, body #3, of another material. The specification is

A = +1 OR +2
and B = +3 -1 -2 .

Thus, input zone A consists of all spatial points that lie within EITHER body #1 OR body #2. This is an example of input zone specification as a union of bodies.

In Fig. E-10d, the intersection of body #1 and body #2 consists of a single homogeneous material; the rest of the space within body #3 is filled with another material. The specification is

A = +1 +2
and B = +3 -1 OR +3 -2.

Thus, input zone A consists of all spatial points that lie within body #1 AND within body #2.

Note that:

a) The OR operator refers to all following body numbers until the next OR operator is reached or a new input zone is initiated.

b) The AND operator is implied before every body number that is not preceded by an explicit OR operator, except that the first OR operator of a union is an implied EITHER.

E.1.3 Volume Specification -- A general scheme for the precise calculation of the volumes of input zones defined by the combinatorial method is not possible. The user may select one of three options via [parameter(1)] associated with the GEOMETRY keyword. The default value of 0

will cause the code to set all volumes to 1.0 $cm.^3$ A value of 1 allows the user to read in the volumes as described below. Finally, if the geometry is such that a satisfactory method exists for calculating the volumes internally, the user may set [parameter(1)] equal to 2 and use a correction run to insert the necessary logic at the proper place near the end of Subroutine JOGEN. The proper location is commented in the coding.

E.1.4 Material Specification -- A material index is assigned to each input zone. A zero index defines a void zone; otherwise, the material indices are defined by the order in which the materials are specified in executing the cross section generating code as described in Sec. 2.2.2. The method of inputting the material indices is described under the keyword GEOMETRY.

E.2 Input Data

The geometry input for the ACCEPT codes is inserted according to the following sequence. The data is inserted in free format form with spaces or commas as delimiters. Simple examples can be found in Secs. B.3, B.6 and B.8 of Appendix B.

E.2.1 Body Data -- The body data begin immediately after the line containing the GEOMETRY keyword. The method of describing each of the body types is discussed in Sec. E.1.1 and illustrated in Table E-1. The description of each new body must begin a new line of input, and the first parameter on that line must be the appropriate three character code for the body type. Table E-1 lists the additional input parameters required (no defaults) for each body type in their proper sequence. The user is free to distribute these parameters over as many lines as he pleases. A line beginning with the parameter END signals that the description of all of the problem bodies is complete.

E.2.2 Input Zone Data -- Geometrical specification of the input zones begins immediately after the line containing the END parameter for the body data. The method of describing the input zones in terms of the input bodies is discussed in Sec. E.1.2. Body numbers are determined by the order in which the bodies are read in. The description of each new input zone must begin on a new line of input, and the first parameter on that line must be a character string beginning with the letter Z. This parameter is followed by a string of parameters that specifies the input zone following the form of the right hand sides of the equations of Sec. E.1.2. For example, input

Table E-1: Data Required to Described Each Body Type

Body Type	Real Data Defining Particular Body					
BOX	Vx	Vy	Vz	A1x	A1y	A1z
	A2x	A2y	A2z	A3x	A3y	A3z
RPP	Xmin	Xmax	Ymin	Ymax	Zmin	Zmax
SPH	Vx	Vy	Vz	R		
RCC	Vx	Vy	Vz	Hx	Hy	Hz
	R					
REC	Vx	Vy	Vz	Hx	Hy	Hz
	R1x	R1y	R1z	R2x	R2y	R2z
ELL	V1x	V1y	V1z	V2x	V2y	V2z
	R					
TRC	Vx	Vy	Vz	Hx	Hy	Hz
	R1	R2				
WED	Vx	Vy	Vz	A1x	A1y	A1z
	A2x	A2y	A2z	A3x	A3y	A3z
ARB	V1x	V1y	V1z	V2x	V2y	V2z
	V3x	V3y	V3z	V4x	V4y	V4z
	V5x	V5y	V5z	V6x	V6y	V6z
	V7x	V7y	V7z	V8x	V8y	V8z
	Face Descriptions (see note below)					
END	No Data					

Note: The final line of the arbitrary polyhedron input contains a four-digit real number for each of the faces. Thirty data values are required for this body type; if there are fewer than eight corners and six faces, zero values must be entered. See Section E.1.1 for more details.

lines describing the two input zones in Fig. E-10d are

```
ZOO1 +1 +2
ZOO2 +3 -1 OR +3 -2  .
```

The user is free to distribute the parameters necessary for describing an input zone over as many lines as he pleases. A line beginning with the parameter END signals that the description of all of the problem input zones is complete.

E.2.3 Volume Data -- If [parameter(1)] associated with the GEOMETRY keyword is equal to 1, the array containing the volume data is inserted immediately after the line containing the END parameter for the data specifying the geometry of the input zones. The input zones are numbered according to the order in which they are read in. The array must contain an entry for each input zone (no defaults). If [parameter(1)] is not equal to 1, these input data are omitted.

E.2.4 Material Data -- For input of material data, return to the discussion under the GEOMETRY keyword.

APPENDIX F. PARTICLE WEIGHT

ITS uses a Monte Carlo approach that often does not exactly simulate physical transport. For instance, each ITS particle might represent a number W of particles emitted from a source. Here, W is the initial weight of the ITS particle. In an exact simulation, the W physical particles would each have a different random walk, but the ITS particle representing these W physical particles will only have one random walk. Many particles of weight W are initiated and followed producing statistically identical results. Although this is not an exact simulation, weight is preserved in ITS in the sense of statistical averages and therefore in the limit of large particle numbers (including particle production or losses that may occur). Each ITS particle weight is tallied so that the final results (tallies) reflect the results expected from W physical particles. (Weights do not have to be integers!) This allows users to normalize the output to the desired source strength. ITS results are normalized to the number of incident source particles. [Ref. 8: pp. 53-54]

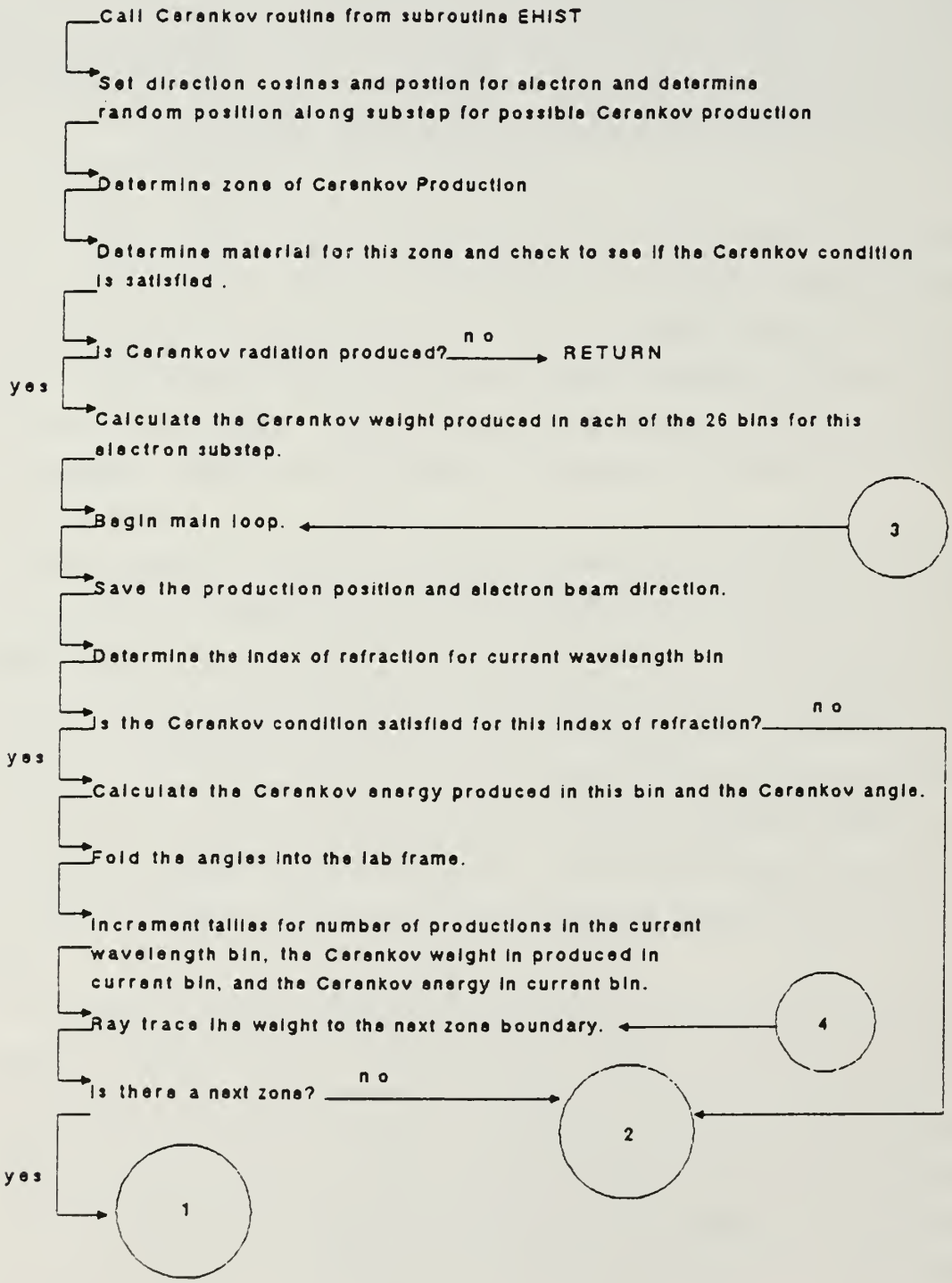
As an example, the Cerenkov routines in this work calculate the total number of Cerenkov photons produced for each electron substep (small pathlength). Rather than tracking each of these photons individually, a random position along the substep is selected as a representative production site and a Cerenkov photon of appropriate weight is generated. This photon weight represents all Cerenkov photons generated over this pathlength. This weight is then multiplied by the parent electron weight (corresponding to the number of electrons represented by the ITS electron taking the substep), and the final weight is assigned to the Cerenkov photon. The photon is then ray traced through the problem geometry. Then the next electron substep is taken and the process is repeated.

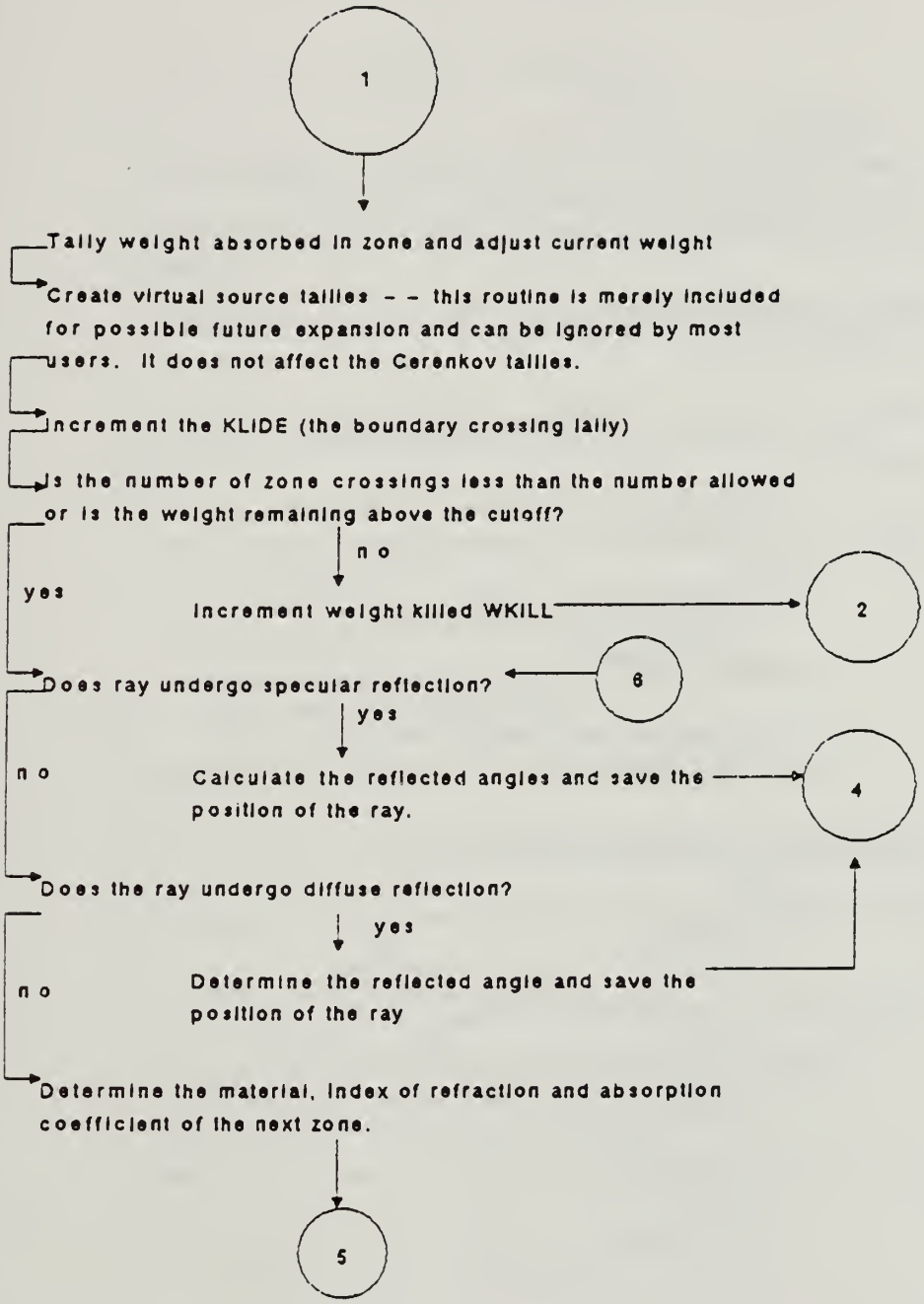
The utility of particle weight does not rest solely upon normalizing the source. Weight is a critical tool used in biasing problems to improve computational efficiency. For example, a user may be interested in studying the results of an interaction that has a small probability to occur. Normally, this interaction is seldom sampled and necessitates large numbers of histories to get a statistically significant result. A better approach would be to increase the sampling frequency for longer wavelengths with a corresponding weight adjustment in the interaction. This can be done efficiently, providing a higher

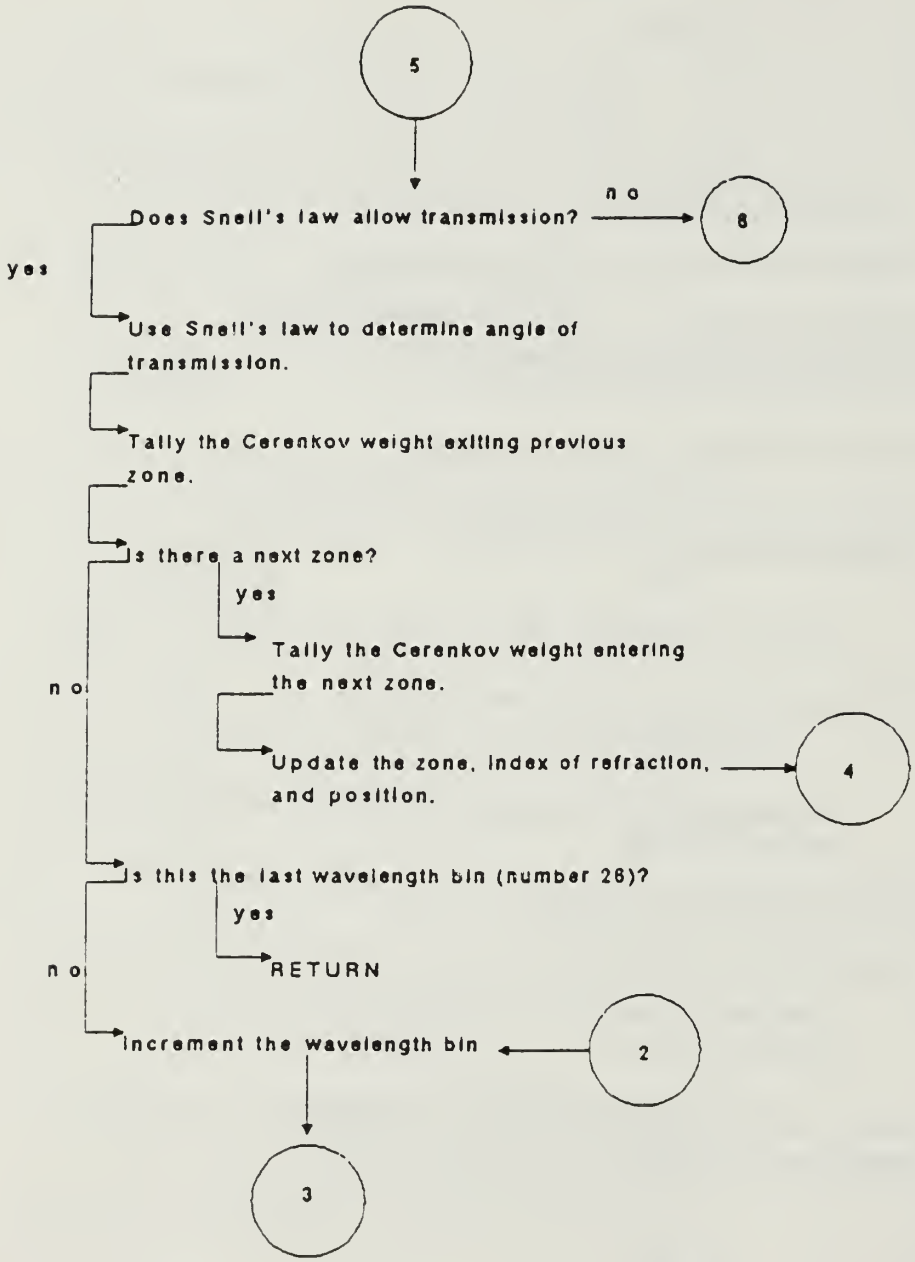
figure of merit, if care is taken to alter the results so that the biasing is removed before scoring.

Summarizing, weight represents the ITS particle's relative contribution to the final tallies. Its magnitude ensures that the expected physical results are preserved in the sense of statistical averages and therefore in the limit of large numbers of ITS particles. Weight enables the user to control the number of particles, sampling the critical part of a problem to improve the accuracy of selected results. Biasing used with weight control can often yield significantly improved figures of merit. [Ref. 8: p. 54]

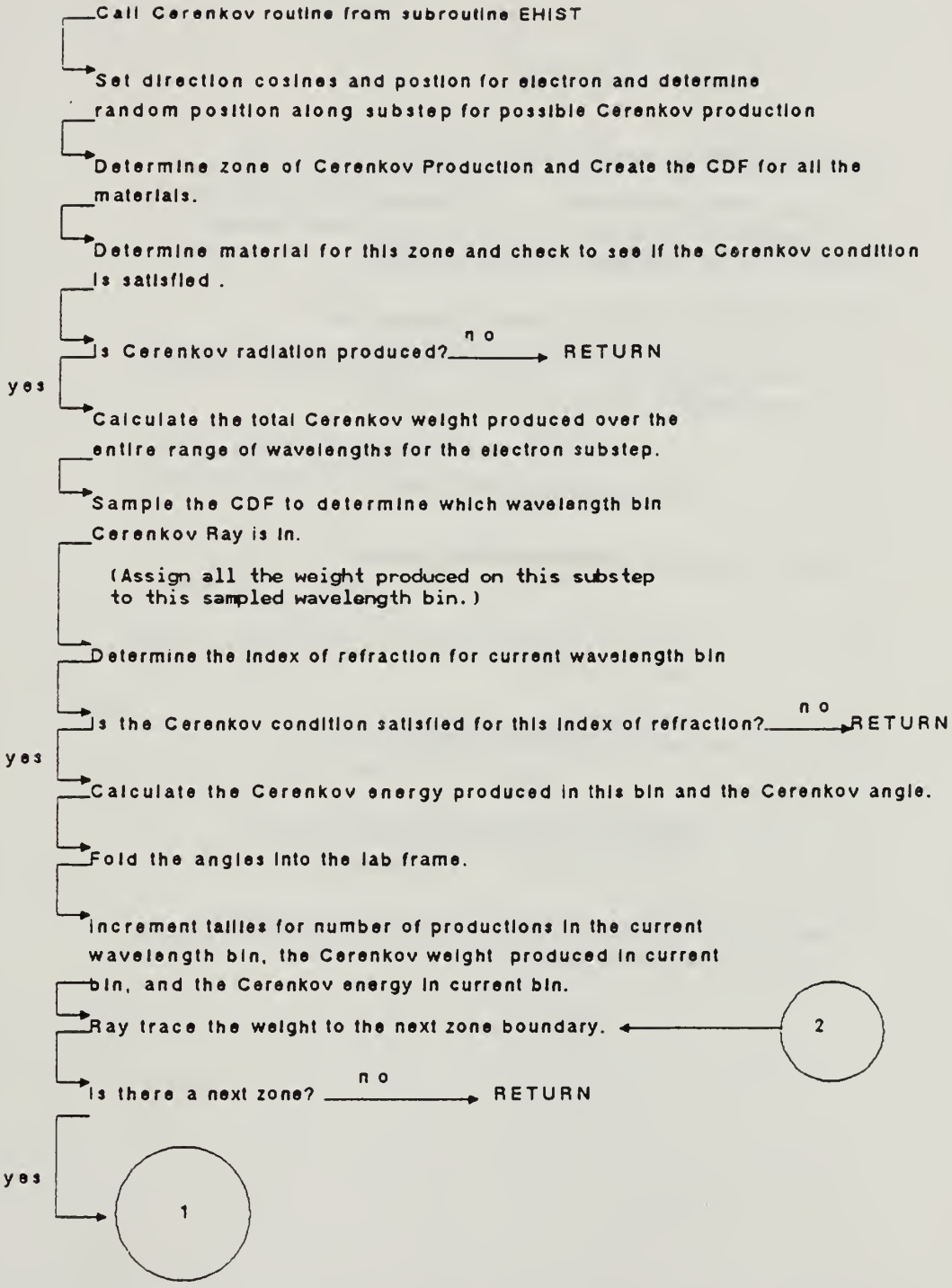
APPENDIX G. MT FLOW DIAGRAM

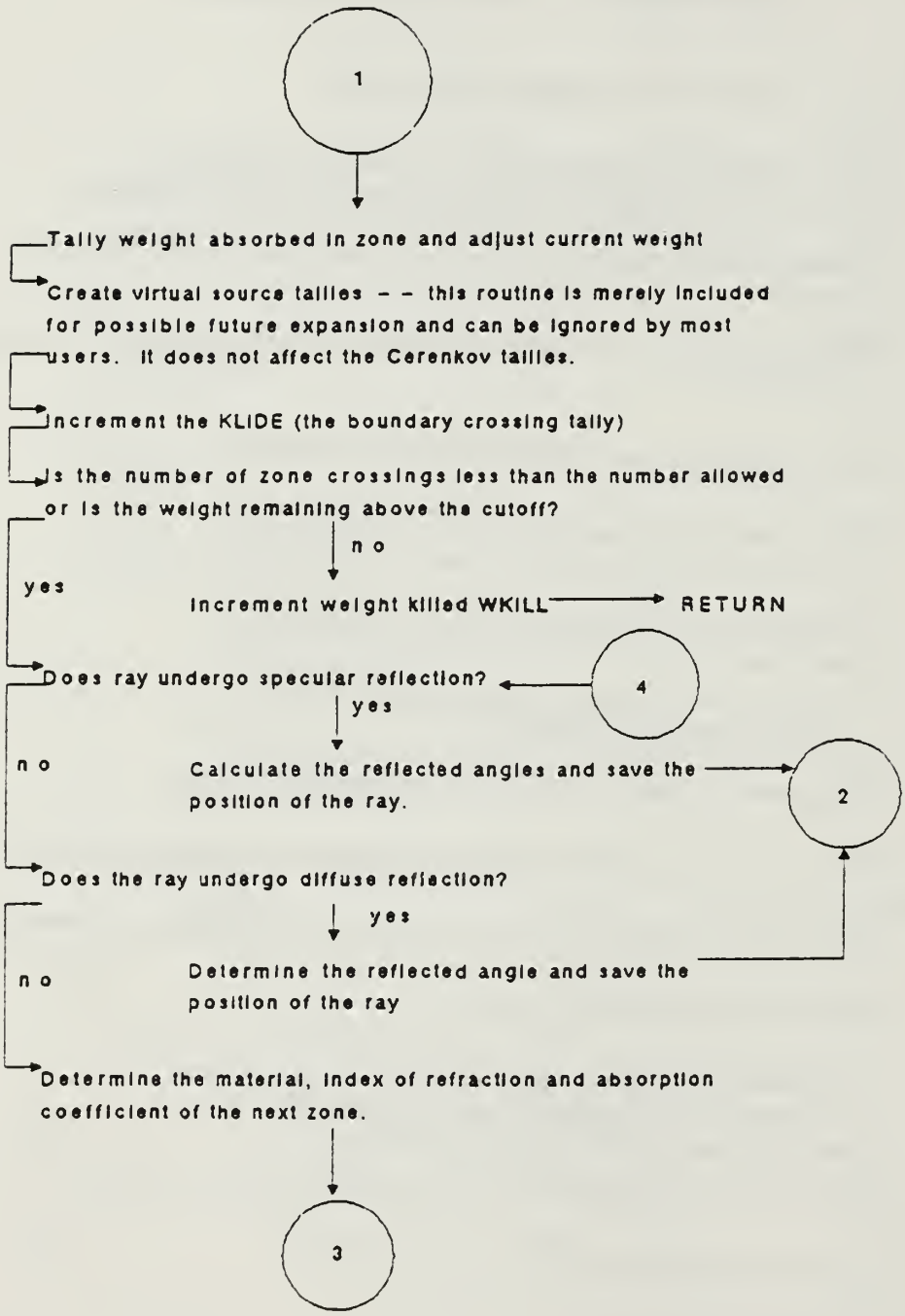

Call Cerenkov routine from subroutine EHIST
Set direction cosines and postion for electron and determine random position along substep for possible Cerenkov production
Determine zone of Cerenkov Production
Determine material for this zone and check to see if the Cerenkov condition is satisfied .
Is Cerenkov radiation produced?
no
RETURN
yes
Calculate the Cerenkov weight produced in each of the 26 bins for this electron substep.
Begin main loop.
3
Save the production position and electron beam direction.
Determine the index of refraction for current wavelength bin
Is the Cerenkov condition satisfied for this index of refraction?
no
yes
Calculate the Cerenkov energy produced in this bin and the Cerenkov angle.
Fold the angles into the lab frame.
Increment tallies for number of productions in the current wavelength bin, the Cerenkov weight in produced in current bin, and the Cerenkov energy in current bin.
Ray trace the weight to the next zone boundary.
4
Is there a next zone?
no
2
yes
1

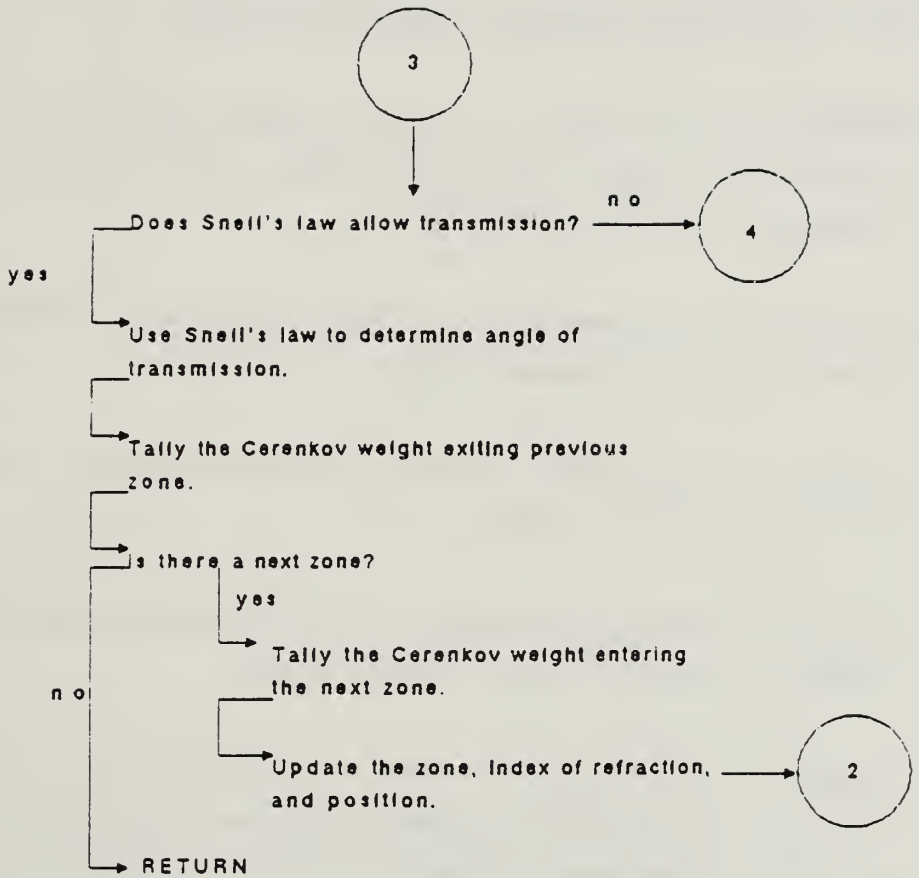

1
Tally weight absorbed in zone and adjust current weight
Create virtual source tallies -- this routine is merely included for possible future expansion and can be ignored by most users. It does not affect the Cerenkov tallies.
Increment the KLIDE (the boundary crossing tally)
Is the number of zone crossings less than the number allowed or is the weight remaining above the cutoff?
n o
yes
Increment weight killed WKILL
2
6
Does ray undergo specular reflection?
yes
n o
Calculate the reflected angles and save the position of the ray.
4
Does the ray undergo diffuse reflection?
yes
n o
Determine the reflected angle and save the position of the ray
Determine the material, index of refraction and absorption coefficient of the next zone.
5


5
Does Snell's law allow transmission?
no
6
yes
Use Snell's law to determine angle of transmission.
Tally the Cerenkov weight exiting previous zone.
Is there a next zone?
yes
Tally the Cerenkov weight entering the next zone.
no
Update the zone, index of refraction, and position.
4
Is this the last wavelength bin (number 28)?
yes
RETURN
no
Increment the wavelength bin
2
3

APPENDIX H. DS FLOW DIAGRAM


Call Cerenkov routine from subroutine EHIST
Set direction cosines and postion for electron and determine random position along substep for possible Cerenkov production
Determine zone of Cerenkov Production and Create the CDF for all the materials.
Determine material for this zone and check to see if the Cerenkov condition is satisfied .
Is Cerenkov radiation produced?
no
RETURN
yes
Calculate the total Cerenkov weight produced over the entire range of wavelengths for the electron substep.
Sample the CDF to determine which wavelength bin Cerenkov Ray is in.
(Assign all the weight produced on this substep to this sampled wavelength bin.)
Determine the index of refraction for current wavelength bin
Is the Cerenkov condition satisfied for this index of refraction?
no
RETURN
yes
Calculate the Cerenkov energy produced in this bin and the Cerenkov angle.
Fold the angles into the lab frame.
Increment tallies for number of productions in the current wavelength bin, the Cerenkov weight produced in current bin, and the Cerenkov energy in current bin.
Ray trace the weight to the next zone boundary.
2
Is there a next zone?
no
RETURN
yes
1


1
Tally weight absorbed in zone and adjust current weight
Create virtual source tallies -- this routine is merely included for possible future expansion and can be ignored by most users. It does not affect the Cerenkov tallies.
Increment the KLIDE (the boundary crossing tally)
Is the number of zone crossings less than the number allowed or is the weight remaining above the cutoff?
n o
yes
Increment weight killed WKILL
RETURN
Does ray undergo specular reflection?
4
yes
n o
Calculate the reflected angles and save the position of the ray.
2
Does the ray undergo diffuse reflection?
yes
n o
Determine the reflected angle and save the position of the ray
Determine the material, index of refraction and absorption coefficient of the next zone.
3


3
Does Snell's law allow transmission?
n o
4
yes
Use Snell's law to determine angle of transmission.
Tally the Cerenkov weight exiting previous zone.
Is there a next zone?
yes
Tally the Cerenkov weight entering the next zone.
n o
Update the zone, index of refraction, and position.
2
RETURN

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